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Shedding light on GIS: A 3D immersive approach to urban lightscape integration into GIS

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**M.A. Thesis submitted
to the Eberly College of Arts and Sciences
at West Virginia University**

**in partial fulfillment of the requirements for the degree of
Master of Arts in
Department of Geology & Geography**

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ABSTRACT

Shedding light on GIS: A 3D immersive approach to urban lightscape integration into GIS

Andrew Kaufman

Geographic Information Systems (GIS) have the ability to map, model, and analyze real world data and phenomena, and yet visibility and lighting conditions are rarely considered or researched in Geographic Information Science (GISci). Lighting technologies have been created and implemented to overcome the darkness of night and other issues of visibility, and in no place is that more evident than urban areas. Though not researched heavily in GIS, it is now possible to model and analyze lighting of the built environment using GIS, 3D modeling and rendering software. This thesis explores the night time urban lightscape, its spatial aspects and contribution to place as well as its incorporation into GIS and GISci. To capture lighting and its multi-dimensional properties, a 3D model was created of the built environment of Morgantown, WV, USA, including the West Virginia University (WVU) campuses and their exterior lighting. The model was completed through the coupling of ESRI's CityEngine and E-on software's LumenRT4 Geodesign plug-in. Lighting data was obtained through the WVU Department of Construction and Design in the form of a CAD map. After geo-referencing CAD-based exterior lighting data, a raster lighting analysis of WVU's Evansdale Campus was produced to identify under-lit areas. These areas were then redesigned using a lighting design tool and incorporated 3D modeling, GIS, and procedural rule-based modeling. An original workflow was designed consisting of ArcGIS, SketchUp, CityEngine, and LumenRT 4 Geodesign. Lighting scenarios were subsequently viewed and experienced through immersive technologies.

Dedications

I would like to dedicate this thesis to my loving wife Colleen, for moving to West Virginia with me and for her encouragement, love and support throughout graduate school and for many more years to come.

I would also like to dedicate this thesis to my parents, Cheryl and Andy, for all of their hard work in order to give me a great life, and for all their love, patience and help in every way.

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Ch. 1 Introduction

Geographic Information Systems (GIS) have the ability to map, model, and analyze real world data, and phenomena, and yet visibility and lighting conditions are rarely considered or researched in Geographic Information Science (GISci). Lighting is a fact of life for all who inhabit the Earth. Every 24 hour cycle of the Earth's orbit brings with it natural lighting changes in which light transitions between varying degrees of light and darkness. Periods of darkness and light can actually occur for days at a time in the higher latitudes (McKnight and Hess, 2005). In addition to natural lighting, atmospheric and weather conditions can also affect natural light and visibility. Atmospheric conditions can vary daily, if not hourly, and visibility and light conditions can be distorted during periods of precipitation, smoke, and fog. Much of human life is spent in conditions that require artificial light. Work undertaken in traditional GIS, however rarely reflects or models anything other than a clear sunlit mid-day.

Lighting has been an essential part of human space throughout time. Humans have adopted lighting technology to overcome the darkness of night and issues of visibility. Before artificial electric lighting devices were developed, humans used fire and torches to see and navigate in the dark. Fire was essential to life as a means of heating, cooking, bathing in warm water, and for protection. Many places, both rural and especially urban areas, were considered unsafe at night or during conditions of poor atmospheric conditions. Perceived notions of higher crime rates and susceptibility to personal harm tended to, and still does today, confine people inside their homes or to places they feel are safe from nocturnal animals as well as human predators (England and Simon 2010; Pain, 2006). Many stories relate how the human mind can run wild with mystic fears based on tales of the dangers lurking in the dark and the fear of being

lost or harmed (Jakle, 2001). Eventually street lights, though initially primitively designed, became central to urban life. Fuels such as oil, gas, and coal replaced primitive candles, and the use of hand-held lanterns for individual travel became popular. In the mid to late 19th century, electricity provided illumination through the newly invented arc-lamp (Jakle, 2001), and during the 20th century inventors and scientists developed lighting technology ranging from the filament bulb to high pressure sodium and high pressure mercury vapor lights and light-emitting diodes (LED).

During the industrialization of the 19th century and early 20th century in the U.S. and Europe, workers necessarily lived close to their place of employment in urban areas. The smoke and pollution generated by factories, combined with the lack of sanitation laws polluted the air resulting in poor visibility, poor air quality, and smog. For the workers and their families who lived and worked in industrial towns, the conditions were so bad that street lighting was needed to see and navigate even during day light hours (Figure 1).



**Figure 1. Noon time smog requiring lighting adaptations-
Donora, PA 1948.**

www.geography.hunter.cuny.edu/tbw/ncc/Notes/chapter12.humans.env.fall.2011/air.pollution/donora.penn.mid.day.jpg

By the 1950's, the automobile demanded features such as traffic signals, and street lighting became a prevalent feature of the modern urban built environment.

Anthropogenic lighting technologies have extended our ability to participate in activities and travel that were once limited to daytime hours. Many people are no longer limited in their activities by the dark, and outdoor recreational activities such as jogging, walking, and sports are often played under the bright lights of stadiums and fields. Monday Night Football would never be possible, let alone become a household name, without anthropogenic adaptive illumination. Anthropogenic adaptation to darkness in the industrial west has changed the daily temporal face of the world and is comparable in impact to the advent of air conditioning on the population distribution and growth of the sun-belt regions of the U.S. south-east, and south-west.

Anthropogenic lighting has become almost synonymous with cities and urban life in the developed world, though in developing nations and rural areas lighting is not so common and produces differing nocturnal experiences. So dominating is the effect of lighting that many cities The lights on the Las Vegas Strip (Figure 2) and Times Square in New York City (Figure 3) are two of many examples whereby lighting has defined place. Lighting for aesthetic use on buildings, skyscrapers, and signs, has given us new urban landscapes. Artificial lighting and atmospheric conditions can also influence experiential perceptions and sense of place (Jakle,

Figure 2. (Top) Lights of the Las Vegas Strip -Las Vegas, NV. <http://vitalvegas.com/10-best-views-las-vegas/>



Figure 3. (Bottom) The lights of Times Square- NYC, NY http://www.hanstravel.com/x/?mid=b8&listStyle=gallery&document_srl=1287



2001). During the day, and under clear conditions, the geographies and places that we see and experience appear differently than they do with night time illumination or non-illumination. The geography of the artificially illuminated environment can produce a new sense of place, experiential qualities, and varying characteristics.

Lighting has become the technological solution to natural darkness and times of impaired atmospheric visibility. Over-illumination of the built environment, however, can result in light pollution, and high energy consumption. Despite these negative aspects, artificial lighting has become a central part of daily life for most urban dwellers, and a necessity and asset that is often taken for granted as being part of urban landscapes. When lighting, as a result of failure, becomes temporarily disabled the disruption in our everyday activities is profound.

In New York City during Super Storm Sandy in October 2012, for example, urban residents suffered mass power outages due to the impact of the hurricane and suffered considerable hardships (Figures 4 & 5). Lighting

conditions are not uniform across the built environment. Residential neighborhoods are usually less well lit compared to commercial districts with extensive neon lights and lit store fronts, as

Figure 4. – New York City without power during Hurricane Sandy. October 2012

<http://articles.latimes.com/2012/oct/31/nation/la-na-nn-new-york-marathon-sandy-20121030>

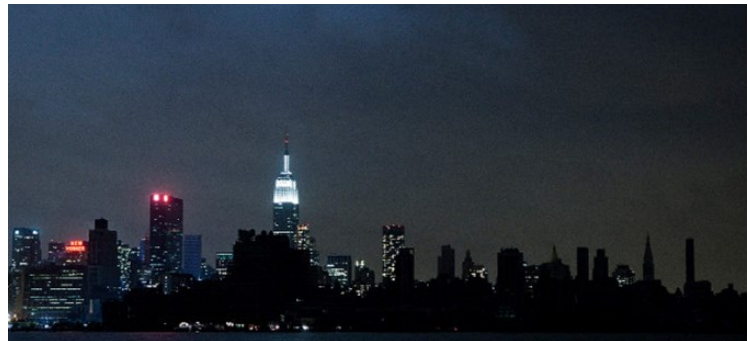
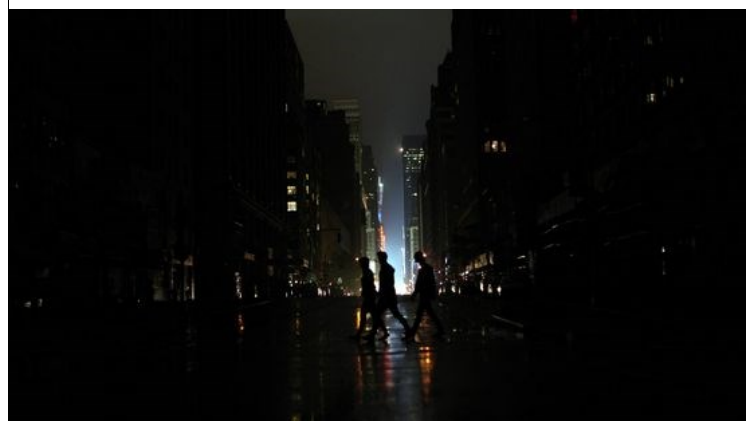


Figure 5. - Urban dwellers of New York city, coping with no power in wake of the Sandy's aftermath

<http://www.theatlantic.com/infocus/2012/10/hurricane-sandy-after-landfall/100396/>



well as additional street lighting for pedestrian safety. Aesthetic lighting, street lighting, and visibility are thus all components that make up the urban lightscape.

Lightscales oscillate between natural daylight and anthropogenic lighting. Urban lightscales have powerful experiential qualities which have been captured through art, and philosophy, but not so much in GIS. Vincent Van Gogh once said “I often think that the night is more alive and more richly colored than the day”. His paintings “Starry Night” (1889), & “Starry Night Over the Rhone” (1888) (Figures 6 & 7), comprising city skylines with gas lamps burning for light, and the reflectance of the lights in the Rhone River with the stars and moon brightly glowing above, are prime examples of humans seeking to capture a sense of place that comes with the night and the human desire to illuminate the built environment. Photographer Stephen Wilkes, for example used low light images taken sequentially every few minutes, from the same fixed location throughout a 24 hour cycle to create a transition of illumination, captured in one image, showing the changing lightscales of the built environment. (Figures 8 & 9).

Anthropogenic illumination is a key feature of lightscales, but is not the only factor. Visibility and atmospheric conditions play key roles in lightscales as well.



Figure 6 (Top) “Starry Night” (1889), & Figure 7 (Bottom) “Starry Night Over the Rhone” (1888)
<http://www.vangoghgallery.com/painting/starry-night.html>



Fig. 8 Coney Island, New York City: Day-Night Transition by Stephen Wilkes

<http://www.stephenwilkes.com/fin e-art/day-to-night/>



Fig. 9 Shanghai, China: Day-Night Transition by Stephen Wilkes

<http://www.stephenwilkes.com/fin e-art/day-to-night/>

Natural conditions such as fog (Figure 10) and rain can have cognitive and experiential qualities such as Niagara Falls, which has a thick water vapor layer in the air due to the force of the water going over the falls. Wild fires (Figure 11) and forest fires can cause thick smoke and redden the skies from the reflection of the fire bouncing off the low smoke cloud layer. Artificial lighting conditions such as smog as well as a clear sunny day can have experiential qualities as lighting conditions affect the cognitive well-being of an individual as well as provide a sense of place.



Figure 10.

***Fog and night time
illumination of the built
environment
Toronto, Ontario, CA***

<http://forum.skyscraperpage.com/showthread.php?t=157136&page=3>



Figure 11.

***Orange and Red skies due to
wildfire
Witch Creek Wildfire,
Escondido, CA 2007***

<http://www.cityandcoastproperties.com/Web/AR475665/CustomContent/index/5471133>

Yi-Fu Tuan (1974), in his book “Topophilia”, discussed how perception and experience have cognitive effects on individuals regarding their understanding and experience of place, and in his 1977 book, “Space and Place: the perspective of experience”, Tuan discusses the important role of visibility in the creation of place. While Tuan does not mention lighting specifically, lighting in the built environment can be viewed as both a ‘placial’ phenomenon, meaning that the lighting

gives or contributes to that specific city's sense of place and character, as well as a spatial phenomenon, implying that the light coverage as well as its planning and design have a spatial component that can be analyzed and modeled.

Currently, GIS has very limited ability to model any variance in lighting conditions, other than an assumed perfect midday visibility. Furthermore, GIS is predominately a 2D platform whereas modeling lightscapes requires a 3D built environment to capture how structures block light, cast shadows and reflect ambient lighting conditions. There are no specific lighting tool packs in ArcGIS for modeling diurnal or anthropogenic lighting adaptations or varying atmospheric conditions. In reality the few approaches to modeling light conditions have been in the areas of remote sensing, serious gaming engines, and 3D GIS. It is well known that GIS can be used to analyze and model spatial phenomena, however this study not only models and analyzes the spatial components of light but also uses GIS and other technologies to address the questions of modeling and analyzing the placial aspects of light for the re-creation of the experiential characteristics associated with natural and artificial lighting of the built environment, GIS tends to focus on the spatial to the detriment of place. This study seeks to redress this imbalance by focusing on light which is an important characteristic of place making.

Research Goals and Questions

The overall goal of this research is to explore how varied lighting conditions, both natural and anthropogenic, which make up the lightscape, can be represented, analyzed, visualized, and experienced in GIS using 3D Modeling, and Immersive Geography. The research questions that drive this goal are:

1. What are the elements that make up lightscales ?

Three components of lightscales were explored:

- a. Natural lighting
 - i. Diurnal, sunlight, moonlight, reflected light, shadow
- b. Anthropogenic adaptations and artificial light
 - i. Street lights, illuminated windows, aesthetic lighting, ambient light, flood lighting
- c. Atmospheric conditions and light
 - i. Weather, precipitation, fog, smog, smoke, snow, inversion layers, dust storms

2. What studies have previously been undertaken to explore diurnal, anthropogenic, and atmospheric lighting in GIS?

- a. Reviewed the literature
- b. Illustrated lighting issues through real world scenarios and applications
- c. Identify urban applications where the incorporation of natural and anthropogenic light conditions in GIS would potentially be valuable

3. How are aspects of lighting and visibility currently addressed in GIS?

- a. Examine how lighting conditions in GIS and Remote Sensing are currently addressed.
- b. Identify current technologies used to study lighting in geospatial applications.

4. How might diurnal and anthropogenic lighting conditions be incorporated into GIS

- a. Examine the application of LumenRT and GeoWeb 3D in a tight coupling with CityEngine to add lightscales to GIS in urban applications

5. Using a case study of WVU's Evansdale campus, Morgantown, WV, develop a 3D lightscape model to visualize, test, and analyze the incorporation of lightscares into GIS

- a. Set up City Engine, SketchUp, ArcGIS, and populate the database
- b. Prepare the CAVE to display and couple these software
- c. Create 3D models of the campus using CityEngine and SketchUp
- d. Generate a light source layer from Engineering CAD drawings
- e. Add LumenRT lighting effects to CityEngine for display and analysis

6. Using the Evansdale Case Study:

- a. Demonstration through displays, the capability of lightscares using GIS. Demonstrated by: Capturing natural diurnal, anthropogenic, and atmospheric lighting.
- b. Perform geo-processing analysis using 3D Analyst:
 - i. Lightshed analysis based on 3D models of the built environment under changing lighting conditions
 - ii. Illuminance analysis
 - iii. Identify well lit and under-lit areas on campus based on those illuminance calculations
 - iv. Use the procedural modeling of CityEngine and LumenRT 4 Geodesign to display various lighting scenarios

7. Evaluation of the findings and utility of lightscapes in GIS as explored in a 3D immersive environment

- a. Is 3D geo-processing of a GIS based lightscape analysis possible and of value?
- b. Is it possible to perform calculations to determine luminance, and obtain quantitative results for display in GIS?
- c. Is it possible to pursue geospatial applications in a built environment where lightscapes are part of the analytical framework?

Methodology

The initial phase of this study is focused on the preparation of the necessary data layers to be prepared for input which included street light locations, terrain models, building footprints with associated attribute data, static 3D models, and ground cover imagery. Several data layers were incorporated into City Engine and procedural rules using the .cga language and Python scripting were prepared to process the 3D models. The logical sequencing of the .cga rule base was examined through visual inspection to seek any errors in the rule base. Adjustments to the rule base and attribute tables were subsequently made. The point lighting geometry was processed using LumenRT to create anthropogenic lighting conditions. Ambient lighting from windows and other elements of the lightscape were modeled using LumenRT.

At this point the system demonstrates an ability to process several components of lightscape including both the natural and diurnal transition of natural light and anthropogenic lighting. Specifically the 3D characteristics of lightscapes in GIS were addressed by (1) modeling the diurnal transition of lighting conditions from sunrise to sunset and including

moonlit conditions, and (2) modeling anthropogenic lighting adaptations consisting of street lighting, pedestrian walkway lighting, illuminated windows, light reflectivity from building windows, and emergency lighting.

The geo-processing capability of ESRI 3D Analyst was used to perform and display the geospatial modeling of lightscares and light source illumination coverage within City Engine and ArcGIS.

Specifically this study sought to demonstrate the visibility of:

- i. Lightshed analysis based on 3D models of the built environment under changing lighting conditions
- ii. Illuminance analysis
- iii. Identifying well lit and under-lit areas on campus based on luminance calculations
- iv. Using procedural modeling in CityEngine to display lighting scenarios

To this end, point light sources were processed based on lighting fixture parameters developed by the WVU Department of Design and Construction Guide for Standards of Exterior Lighting, and specific bulb type characteristics, to create luminance derived lightsheds. Python scripting was used to automate lightsheds for each light point. All the lightsheds were then incorporated into an illuminance analysis raster, which was classified into categories of light coverage such as well lit, under-lit, and dark. Areas of poor lighting and darkness were identified as areas suitable for evaluation of optimal light pole placement.

Using procedural modeling in CityEngine, visual lighting scenarios were produced for evaluation as an urban planning and lighting design application. Light points in CityEngine were represented as Illuminating Engineers Society (IES) light models, which have accurate

photometric data for each light fixture type, and bulb type data such as lumens, wattage, and color

([http://docs.autodesk.com/REVITST/2010/ENU/Revit%20Structure%202010%20Users%20Guide/RST/index.html?url=WS73099cc142f487553b93539f117fa9a937a-](http://docs.autodesk.com/REVITST/2010/ENU/Revit%20Structure%202010%20Users%20Guide/RST/index.html?url=WS73099cc142f487553b93539f117fa9a937a-e71.htm,topicNumber=d0e116718)

[e71.htm,topicNumber=d0e116718](http://docs.autodesk.com/REVITST/2010/ENU/Revit%20Structure%202010%20Users%20Guide/RST/index.html?url=WS73099cc142f487553b93539f117fa9a937a-e71.htm,topicNumber=d0e116718)). Visual analysis of proposed lighting changes were performed under varied conditions of natural lighting and anthropogenic lighting. The lightscape models were then output to the LumenRT Live Cube. From there the output scenes were displayed and explored at the pedestrian scale, using a Computer Assisted Virtual Environment (CAVE) system, in which lighting and visibility can be represented, analyzed, visualized, and experienced through immersive GIS.

Case Study

Using the case study of WVU's Evansdale Campus, Morgantown, West Virginia, USA, 3D models of structures were coupled with the LumenRT4 Geodesign rendering environment to demonstrate the main components of lightscape, for (i) The natural diurnal transition of light and (ii) Anthropogenic Lighting. The study also demonstrates the utility of the software and workflow for lightscape application in GIS. A combination of ArcGIS, SketchUp, City Engine and LumenRT were implemented for use in the CAVE to model the Morgantown built environment and associated lightscares, specifically the study:

1. Demonstrated through displays, the capability to create lightscares using GIS.
 - a. Natural lighting
 - b. Anthropogenic

2. Performed geo-processing analysis using 3D Analyst:
 - a. Lightshed analysis based on 3D models of the built environment under changing lighting conditions
 - b. Illuminance analysis
 - c. Identified well lit and under-lit areas on campus based on illuminance calculations.

Ch. 2 Literature Review

GIScience and approaches to lighting

Remote sensing and low light cameras and sensors have been used in the visible and Ultra Violet bands to view the distribution of anthropogenic lights at night. Lighting at night has been captured on a global scale by satellites such as the Defense Meteorology Satellite Program (DMSP-OLS) and more recently SUOMI-NPP satellites which uses Visible Infrared Imaging Radiometer Suite (VIIRS) (http://www.nasa.gov/mission_pages/NPP/news/earth-at-night.html). The “Earth at Night” images (Figure 12) produced by these satellites have been used for many GIS and geographical applications and studies. Some of these studies include lighting as an indicator of transportation networking, power outages (<http://earthobservatory.nasa.gov/IOTD/view.php?id=78445>), urbanization (Gallo et al. 2004), energy consumption, light pollution (Chalkias, et al., 2006), and political geography such as the North Korea – South Korea Border (Elvidge, et al., 2001), as an indicator of development and

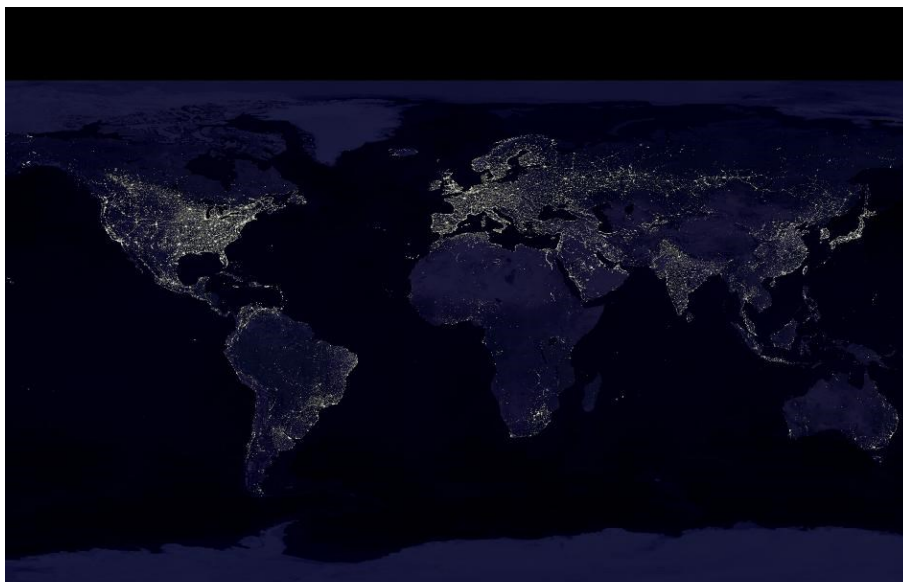


Figure 12, Earth at night NASA 2012

http://www.nasa.gov/mission_pages/NPP/news/earth-at-night.html

human settlement across the global and national scale (Elvidge, et al. 1997), and for land-use and change detection at the city/regional scale (Elvidge et al. 2007). Although, night time

satellite imagery can be applied to many GIS studies, the global scale is too coarse for most lightscape applications. In the “Nightsat Concept”, Elvidge et al. (2007) compare remote sensing technologies with high resolution night time imagery and conclude that DMSP-OLS and VIIRS imagery is good for certain night time illumination studies if the resolution of the images is at the city/regional scale. When the same imagery is re-scaled to the block or street level, the imagery becomes fuzzy and pixelated to the point where the light features are no longer distinguishable. Airborne imagery acquired using a Cirrus DCS camera mounted to a NASA ER-2 aircraft collected data from Los Angeles, CA to Las Vegas, NV in September 2004 to illustrate two major areas of human activity and lighting in areas surrounded by ocean and desert, both of which are extremely dark at night. The noticeable contrast in light and dark helped the assessment by visualizing the sharp boundaries of lit and un-lit areas. The sensors in the camera were also able to distinguish between sodium vapor lights using the NIR band at $0.82\mu\text{m}$, from other light sources (Figure 13). The spectral plots and colors produced by specific lighting types enabled land use patterns to be distinguished, and especially so between residential, commercial, and industrial areas, large boulevards, and smaller residential streets. The images of the city and regions lights were subsequently geo-referenced to the locations and data captured by the spectrometer on the ground, which provided a map of the types of lighting used for different land uses. The ER-2 night time imagery is clear and visible at a scale of 25 meters, and was found to be useful for land-use/land change studies at regional and city scales. Remote sensing is a powerful tool in capturing the Earth’s anthropogenic lighting conditions, but provides only a basis for some coarse scale GIS studies of lighting clusters and patterns.

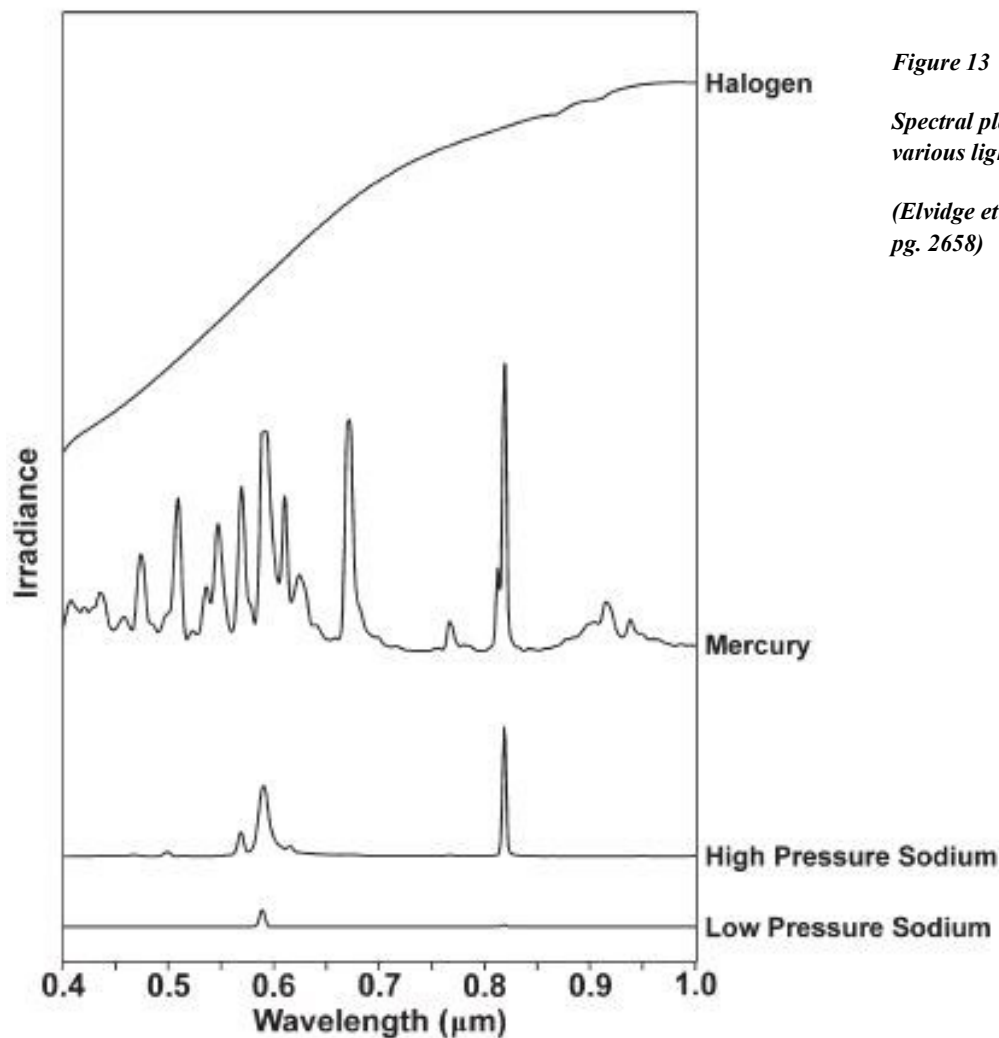


Figure 13
*Spectral plot of
various lighting types*
*(Elvidge et al. 2007
pg. 2658)*

Currently most GIS studies on lighting are invariably focused on the spatial location of street lamps for use in street lamp utility networks, transportation studies, urban planning, and design (Saraji et al., 2009). Data on street lighting can be hard to acquire due to the proprietary nature of the utility companies and local governments that own the data. However, this is not the case everywhere. For example, Montgomery County, Maryland, USA, has made the locations of their street lights available on an interactive map (Figure 14) that allows community members to report non-functioning lights and other issues (<http://www2.montgomerycountymd.gov/dot-streetlight/>). Similarly, the County of Los Angeles, Department of Public Works, Survey/Mapping and Property Management Division, has made a

shapefile dataset of the location of every street lamp in the city of Los Angeles available to the public ([www.http://egis3.lacounty.gov/dataportal/2011/01/27/street-lights/](http://egis3.lacounty.gov/dataportal/2011/01/27/street-lights/)). Attribute data includes x,y coordinates, pole type, lumens, and wattage for each discrete point and 2D vector representations of each light point. However, the two dimensional view is limited concerning the geovisualization of lightscares or incorporation of the dynamic diurnal changes of natural light and anthropogenic lighting, and the various atmospheric conditions and their effects on visibility and analysis.

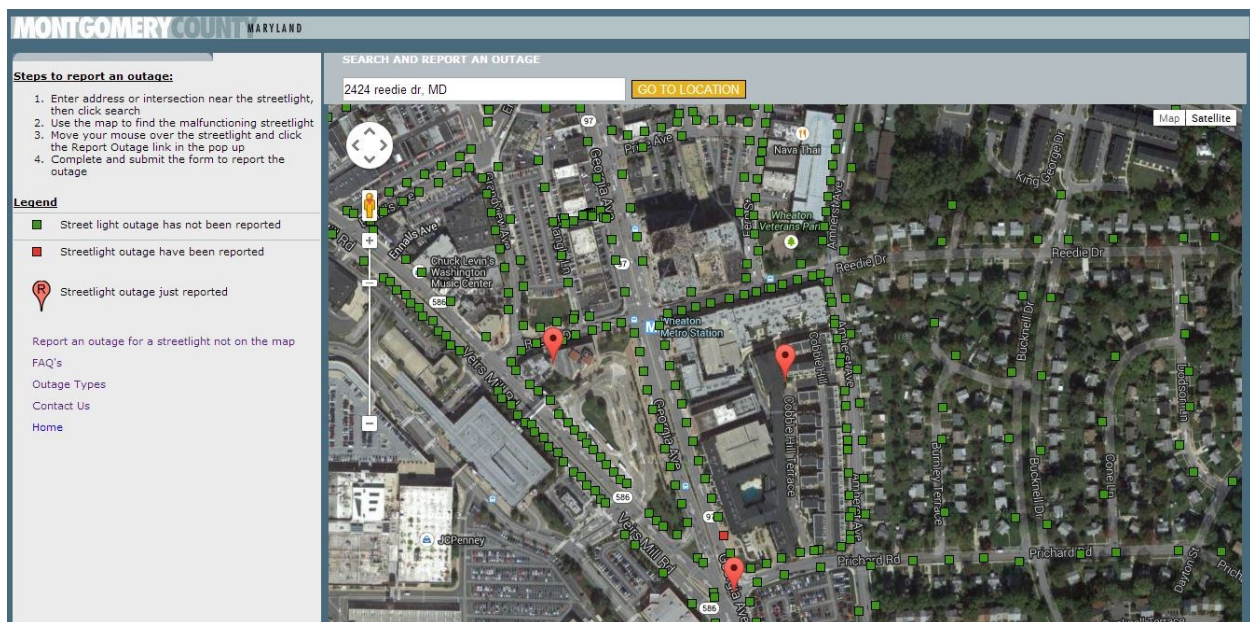


Figure 14 *Montgomery County, Maryland's Interactive Streetlight reporting map*
<http://www2.montgomerycountymd.gov/dot-streetlight/>

Diurnal, Atmospheric, and Anthropogenic Lighting Integration into GIS

Exploring lightscares in GIS to date is thus very limited. Some aspects of lighting can be explored in GIS systems such as ESRI's ArcGIS, using terrain models to create hill shading effects. With a DEM or DTM, ArcScene can model terrain shadowing by adjusting the

azimuthal position of the sun and calendar date settings. ArcScene also allows for limited graphical changes of the sky background or base map to represent different sky conditions at different times of night. There is currently no way in ArcGIS to model, visualize, or analyze ‘realistic’ lighting conditions, atmospheric visibility issues, or anthropogenic lighting for street lights. One possible way to model lightscares is to use serious gaming engines. The ability of serious gaming engines to re-create and visualize lighting has increased and evolved at a faster rate than that of GIS, this is mainly because serious gaming technologies and advancements are driven by the entertainment industry with limited opportunities for spatial analysis and GIS. 3D gaming engines such as Unity 3D (Unity3d.com) can display dynamic lighting that can be cached based on player location, movement, and animation. Unity has settings for lighting as part of the ‘creation tools’. Lighting in Unity can be modeled in four different ways; area lights, point lights, directional light, and spot lights. Area lights are used to light an entire rectangular plane, such as window lights at night. Point lights can be placed anywhere and shine in every direction, similar to the light dispersion of a filament bulb. Directional lighting is used to model sunlight and atmospheric lighting, which could include moon light, sunset and sunrise, and can be filtered and colored to represent lighting changes brought about by haze, clouds, rain or fog. Spot lights can be used to create a light beam in a certain direction with a cone of illumination such as street lamps or building entrance lights. Point lighting can also be set to display a lighting radius at ground level from a given point.

In addition to lighting types, Unity also allows the creator of a scene to alter the characteristics of the lighting model by color, softness, range, distance and x,y extents. Unity allows for dynamic shadow modeling based on the direction of the lighting source and the perspective that the player is facing at any given time

(<http://docs.unity3d.com/Documentation/Components/class-Light.html>). Unity allows for first person navigation in addition to other vantage point settings for navigation at street level. Unity also has settings for physics, which is the term used in gaming engines and virtual reality to denote the modeling of dynamic features, realistic properties, physical characteristics, and their application to real world scenarios. For example, serious gaming engines apply physics such as modeling gravity to keep an avatar grounded, and colliders which simulate what would happen if one were to walk into a virtual wall, rather than pass through it.

Research and exploratory techniques are being used to see if gaming engines could be combined with geographic data and GIS (Herwig and Paar, 2002; Stock et al., 2005). The lighting technologies and tools within gaming engines could potentially make substantial contributions to 3D GIS and light modeling in GIS, however, this is at an early stage in research. One of the drawbacks to using serious gaming engines is that they require high-level programming that many geographers are not familiar with and are out of the realm of most GIS users skillsets. Thus, a pre-designed lighting software or tool pack for GIS, where features of lighting and visibility can be preset through the selection of scenarios and conditions by the user would open new doors for realistic light modeling and analysis in GIS. One such 3D GIS software is Geoweb 3D (<http://www.geoweb3d.com/>).

GeoWeb 3D is a GIS software that has 2D and 3D capabilities. The GeoWeb 3D graphic user interface has tabs similar to web browsers for embedding ArcGIS where the user can simultaneously work in 2D with ArcMap, and with the same data in 3D. With embedded internet, acquiring basemaps from Google or Open Street map is possible, as well as importing SketchUp warehouse 3D models. GeoWeb 3D has variable settings for lighting such as time of day, natural lighting effect, background sky maps, and most importantly built-in point lighting

tools with color editing and preset colors representing various lighting sources, such as mercury vapor, sodium vapor, and halogen. These lighting effects can be set and controlled through the user interface and without any programming or coding involved. Point files can be created through the vector tools, or imported from an existing ArcMap (.mxd), shapefile (.shp), geodatabase (.gdb), or Google (.kmz). This makes for a user-friendly and intuitive way of adding point lighting to 3D GIS and modeling.

Geoweb3D has stereo-vision capability through red-cyan, active, and passive 3D technology, and can be used for multiple screen display, making it a good choice for use in a CAVE or 3D virtual environments. The desire for high quality lighting effects built for a 3D GIS system may soon be achieved through the combination of 3D modeling, 3D GIS, and Real Time Environment Rendering Platforms such as Lumion or LumenRT 4 studio.

Eon-Software's LumenRT 4 Studio is a real-time environment rendering platform that supports imported models from 3D modeling software, architectural design models, and 3D GIS models such as ESRI's CityEngine. LumenRT provides a stage for displaying 3D models with real-world effects, such as point lighting, reflectivity off glass surfaces, water, and sun/moonlight that are calendar synced. Lumen also has the ability to model real-world physics such as wind and its direct effects on objects and models such as trees swaying back and forth in the wind, as well as flowing water. Lumen has animated models such as moving cars, birds, and people, thereby turning a 3D GIS model into a more realistic experience. Lumen RT has a rule based plug-in built directly for ESRI's City Engine, called LumenRT 4 Geodesign, whereby all the capabilities of Lumen RT can be incorporated seamlessly into a City Engine (CE) scene. The real time environment rendering and lighting capabilities combined with the

procedural rules created in CE produce realistic scenes that enable the user to be fully immersed within a 3D GIS lightscape model.

3D Modeling and GIS for Lightscape Analysis

GIScience research attempting to map and/or model lightscapes and visibility in GIS cannot rely solely on current 2D methods to represent this 3D phenomenon. There are many factors associated with lighting that cannot be addressed in a 2D representation for buildings, trees and vegetation, along with other possible objects can obstruct light and visibility, and cast shadows. Reflective materials, such as windows and water features can reflect and refract light in differing directions. Since lighting and visibility are 3D phenomena, one possible method to examine lighting conditions within GIS is to use 3D geovisualization. Geovisualization is a form of scientific visualization heavily reliant on computer technology to view spatial data and to create and explore 3D virtual environments for knowledge production and communication.

3D geovisualization represents and communicates data to the map reader or Virtual Environment (VE) user through 3D modeling and the conversion of 2D maps and geometry into 3D (Nöllenburg, 2007), and generally presents more accurate and complete representations of urban development and the built environment (Xu and Coors 2012). MacEachren and Kraak (2001) state that maps and graphics in a 3 dimensional context doesn't simply make the data viewable, it transforms the data to the point where it can be used as an active tool in the thinking process of the viewer or analyst. MacEachren created a conceptual framework for 3D Geovisualization called the "Map Use Cube" (Figure 15). The cube's X axis represents a scale of interaction with the data from the analyst to a broader audience, the Y axis displays the unknown to well-known metric, and the Z axis displays the level of participation of the intended

audience starting with private (the analyst) to public: from public officials to stakeholders and community members. Starting from the origin of the X,Y,Z axes, the map use cube illustrates the levels of involvement between data exploration and a research goal driven analysis in which relevant information is synthesized, and the results and plans presented. GIS technology and 3D

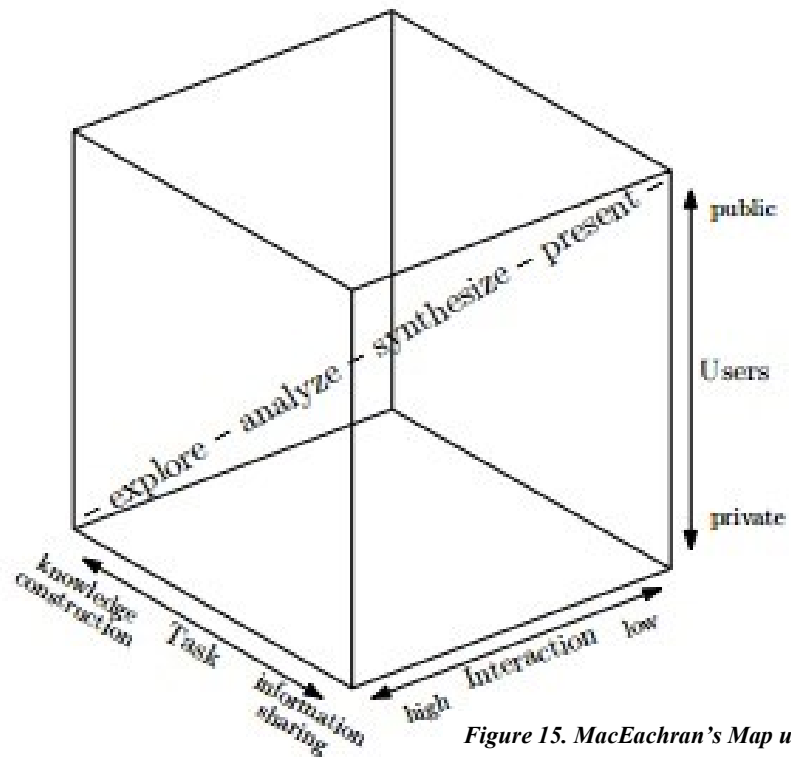


Figure 15. MacEachran's Map use cube
http://www.itc.nl/library/papers_2004/phd/van_elzakker.pdf

geovisualization approaches have been merged into many geographic projects and studies to explore, analyze, and represent real world issues. One of those real world issues could be lightscapes. However, to do so, requires a GIS with built-in 3D modeling and lighting capabilities.

Currently, ArcScene, ArcGlobe (ESRI), Google Earth, (Google), World Wind (NASA), and GeoWeb3D, are 3D GIS platforms that provide some natural lighting capability and can import 3D models such as the models created in Trimble SketchUp. SketchUp is a 3D modeling software that can be used to create highly detailed 3D models. SketchUp has both sun angle and shading options available and atmospheric conditions, and can simulate an opacity layer set by a slide-bar. These models can be created to evaluate and model 3D light, but they have limitations in that they are static models, and only capture one moment in time. To model light, which has

dynamic properties, static models are not the preferred form of lightscape representation, unless the user is trying to capture the lighting of a specific point, time, and place, or the reflections and/or shadows a building may produce. Another limitation of SketchUp is its inability to perform batch modeling. A network of light posts or an entire city of buildings would take too much time for one person to create using SketchUp. Even with copy and paste features, placing the buildings in the correct location in the digital built environment would be time consuming and would have to be done manually.

In order to represent the lightscape of an entire city, batch modeling or procedurally generated buildings are needed. This was recognized by ESRI, who in 2011 acquired CityEngine, and added it to the ESRI suite of GIS software. CityEngine 2012 (ESRI) is a 3D modeling software that has been embraced by GIS and used primarily for urban applications. CityEngine can perform batch modeling and generate an entire modeled city using a rule-based approach, known as procedural modeling. CityEngine can import existing road layers and terrain data from GIS, as well as static 3D models from SketchUp or similar sources. CityEngine also has the ability to generate entire cityscapes in 3D. Using building footprints imported into a CityEngine scene, height values can be called from an attribute file to automatically extrude buildings to their attributed heights, facades, and roof style. Most of this modeling and extrusion is done through computational methods using CityEngine's procedural rules and .cga programming language.

CGA or Computer Generated Architecture shape grammar is used for 3D shape modeling and is based closely on GML shape grammar (Xu and Coors, 2012). This type of programming can re-shape a model or polygon based on existing attribution associated with that data or through user entered parameters called .cga rules. Users can program the processes and

parameters through a model builder and flow chart feature. Once the .cga rules are established and loaded into the scene rules, the user can easily manipulate buildings using a built-in graphical user interface with sliding scales to change values and value ranges. Changes can be applied to one section of a single building or to an entire city. The ability to produce geo-referenced 3D models in batch mode enables entire cityscapes to be generated and is valuable for creating and visualizing the lighting of buildings and street lamps as a basis for exploring changing lighting conditions. Notably though, the software performance can be slowed drastically by large 3D model datasets.

CityEngine supports LiDAR based models for 3D models of buildings, or building footprints for extraction through rule based attribute height values. A high quality dataset model of center city Philadelphia, Pennsylvania, created with 1 meter LiDAR, and Pictometry oblique imagery, is provided with CityEngine 2012 for analysis and extraction. LiDAR can capture 3D phenomena and represent it through a 3D point cloud display. Side-scanning LiDAR can be used to model building frontages, viewsheds and even electric power lines. Some side-scanning LiDAR can also capture color during point data collection which could be used to display night time illumination of buildings, bridges, and streetlamps. LiDAR can be used to create 3D models of buildings which, when coupled with ortho-imagery, can create highly accurate and realistic models of a built urban environment. With further studies and the combination of LiDAR, remote sensing, and 3D GIS, there is potential to model and explore the built environment. However, herein lies a challenge to GIScience, for most 3D GIS platforms do not function well at a street level or first-person scale, and even CityEngine will start to lag when scaling down to street level navigation. Another challenge is viewing high quality city models in a true 3D environment that simulates reality, because most 3D GIS output is displayed and

visualized through a 2D or 2.5D computer monitor. Even navigational functionality within the 3D map lacks a realistic pace and ability to simulate movement as if someone was actually moving in real time and space. In contrast, rendering environment software such as LumenRT 4, have the ability to navigate the scene in first person, as well as with physics, realistic sound, wind, rain, and lighting effects.

Urban planners, GIS professionals, government, and the military, among other fields benefit from 3D immersive GIS analysis and display. Being able to immerse stakeholders as well as planners within a 3D map can transform communication through geovisualization. Experiential qualities such as the phenomenology of lightscape in the built environment can be examined through immersive GIS. GIS, 3D modeling, and the CAVE, have the potential to explore Jakle's (2001) concepts of lighting and place to provide an important component contributing to understanding sense of place, as well as visibility and cognitive associations of lightscapes. Lighting, lightscapes, and visibility can provide experiential qualities, as well as produce cognitive perceptions of a place. Phenomenology and GIS have the potential to complement each other, but they require an immersive environment to capture the full experience of lightscapes. Furthermore, modeling lighting and visibility issues in 3D GIS can also provide a visual representation of lightscapes as well as insight and analysis to the field of urban planning. For example, Koltsova et al. (2012) combined 3D GIS and urban design at the pedestrian scale for design considerations; Podevyn (2013) used 3D GIS and modeling for the creation of a sustainable virtual city plan, and deCastro et al. (2011) automated a computer based algorithm for light modeling within the architectural design framework, and for transportation planning Zhou, et al. (2009). Urban planning for safety can involve lighting and crime patterns, and their correlation to lighting placement overlay analysis (Pain 2006).

This thesis involves 3D modeling, lighting and planning for an urban university campus. Campus planning for 3D building and lighting using GIS and CityEngine has been undertaken by Antunes (2013) at the University Jaume I, Castello, in Spain. CityEngine proved to be a powerful method of visualization for planning and design. Currently West Virginia University is undergoing reconstruction on its extended campus and has placed a heavy emphasis on pedestrian and vehicular improvements, including walking paths, building connectors, parking lots, and traffic and pedestrian lighting. Currently, the building construction phase is taking place, to be followed by pedestrian oriented construction which will involve lighting design and implementation. Planning can be approached through the analytical topologies, and geo-processing capabilities of a GIS and 3D GIS. CityEngine, coupled with LumenRT 4 Geodesign, can provide insight into geovisualization and make a scene look realistic. However, CE and LRT4 lack the geo-processing capabilities within a GIS, which provide the ability to undertake 3D spatial analysis.

3D Geo-processing for Visibility and Lighting Analysis in GIS

Viewshed analysis for visibility in GIS is much different than atmospheric visibility. Where viewshed analysis in ArcGIS accounts for what can be seen from a point based on topography, atmospheric visibility is what is visible and can be seen from a specific location during times of naturally altered visibility such as precipitation, smog, and fog. As with anthropogenic lighting, atmospheric conditions and visibility have yet to be incorporated into traditional GIS. However, visibility analysis and line of sight (LOS) analyses in GIS is still most commonly seen in a 2D map using the visibility toolset in the 3D analyst tool box of ArcMap.

2D visibility tools have analytical capabilities, but in a multidimensional world these tools are limited and their visual output is lackluster. Viewshed analysis has been used in many GIS visibility studies of the urban built environment and for urban planning and design (Yang et al., 2007; Sanders and Manson, 2007). Viewshed analysis takes input data from a raster elevation model and from a known observation point and quantifies visible areas. What is visible is attributed with a 0 (not visible) or 1 (visible), and color coded accordingly. All the geo-processing techniques described in this literature review, take place within the ArcGIS platform, with one exception. GeoWeb 3D has a built-in viewshed tool, that allows the user or analyst to perform on-the-fly viewshed calculations, where a discrete point with a specified height, faces a certain direction and displays a triangular box that will overlay either a red mesh surface for non-visible areas and a green mesh surface for visible areas. This was found to be a more visually effective method of viewshed analysis than ArcGIS.

Line of sight analysis (LOS) is part of the same ArcGIS visibility tool pack and performs a straight line visibility analysis. While viewsheds define what is visible from a location, the line of sight defines whether a specific site is visible from another specific location. This is different than viewshed since it is a yes or no question about visibility, can a specific location be seen from one discrete point to another. Whereas viewshed encompasses all the areas that can or cannot be seen. LOS has been used in urban planning and design studies such as Wilson & Liu's (2008) study of Indianapolis urban parks and emergency lighting. Line of sight analysis uses points, a known observer location, and a target location, and utilizes either a raster or 3D surface model. LOS produces a polyline with binary demarcation for visible and non-visible locations. While this serves as a useful tool for the analysis of visibility, it is still limited in its ability to

produce highly visual models of how the line of sight would look as if being viewed in first person.

Natural lighting and shadow visualization in GIS has typically been limited to background lighting and hill shading. The analysis of natural lighting can be performed using the solar radiation tool in ArcGIS. Solar radiation analysis is a tool that measures the incoming solar radiation and produces ‘sun’ maps which quantify the natural lighting characteristics of certain areas within a 3D environment. Incoming solar radiation has been used for climate studies as well as urban planning and design for the placement of solar panels and urban vegetation studies (Huang, 2009). Using specific sun data, time zone, and location, insolation can be output in a raster form. Insolation is indirectly related to the shadows produced by 3D objects. Sun shadow analysis can also calculate the amount of shadow produced by light being obstructed by a 3D object such as a building, billboard, or tree (Southworth, 2003). Sun shadows are represented as polygons and can be extruded to 3D. Sun shadow analysis has the ability to factor the calendar and position on the Earth relative to the sun which allows for temporal shadow studies, by units of hour, day, or month. This can be useful for optimal placement of solar panels or gardens, or to use the shadow area to identify areas where snow and ice might not melt at the same pace of areas exposed to sunlight.

Many 3D geo-processing derivative products such as viewshed and LOS analysis can be quantified volumetrically and analyzed for visibility studies in GIS, 3D GIS, and 3D modeling. In addition to volumetric and area quantification, the outputs can be a 3D polygon or polyline with z-values. These polygons can be further analyzed and visualized through Boolean-logic based geo-processing within the ArcGIS environment in 3D. While visibility studies are relatively common 3D geo-processing tasks in GIS, the analysis of lighting and lightscape

modeling, and analysis are yet to be directly addressed by GIS. Therefore for this study, a lamp post lighting tool was created using a combination of 3D geo-processing tools and techniques.

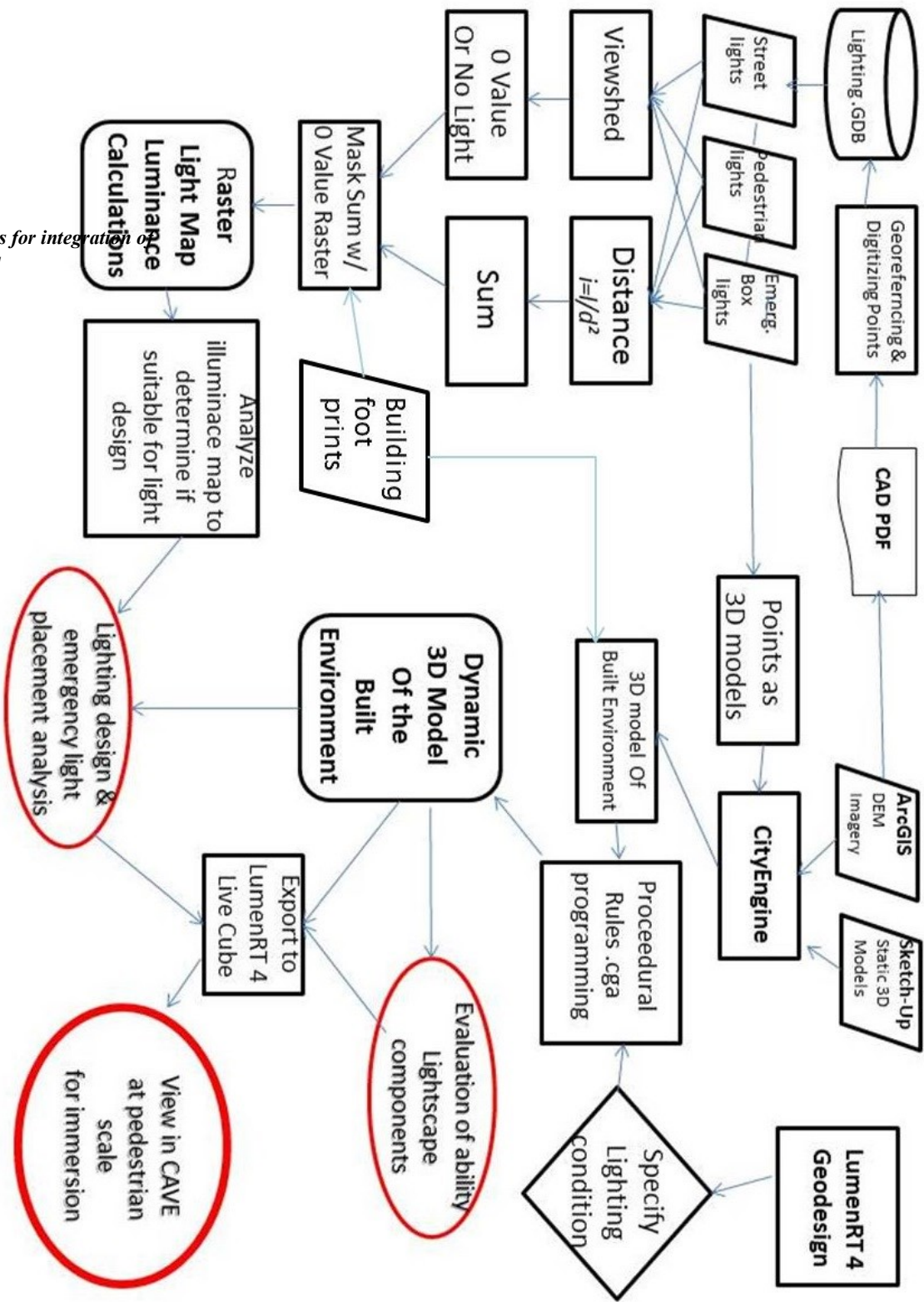
Ch. 3 Data generation, software, and implementation of workflow

Workflow and structural approach

This study combines GIS, 3D modeling, and environment rendering software to model urban lightscares. A workflow for the visualization of lightscape using Arc GIS, SketchUp, City Engine, and LumenRT 4 Geodesign describes a two part methodology in which the outputs of 3D geo-processing are combined with 3D procedural modeling for an immersive perspective on lighting design (Figure 16). First, the creation of a lighting point toolbox for ArcGIS, in which a raster lighting analysis of current lighting and illumination of the area is created, and then analyzed to identify well lit and under-lit or dark areas. Secondly urban lightscares are explored in 3D modeling and GIS. The natural lighting of a 24 hour period is demonstrated, as well as anthropogenic lighting such as streetlamps, pedestrian lighting, emergency lighting, illuminated windows, and vehicular lights.

Areas in the analysis of illumination that were identified as dark or under-lit, were used to evaluate a 3D lighting design and planning assessment. CityEngine and LumenRT 4 Geodesign were coupled to communicate and engage stakeholders with potential lighting scenarios, complete with visual aids as well as quantifiable lighting analysis which could be applied to future studies.

Work Flow For Integration of Lightscape into 3D Immersive GIS



Workflow and Datasets for integration of Lightscape into 3D immersive GIS

Data Sets

The data sets used in this study include:

- 2011 National Agriculture Imagery Program (NAIP) aerial ortho-imagery with a 1 meter resolution. Imagery was obtained from WV GISTC data clearinghouse:
<http://www.wvgis.wvu.edu/data/dataset.php?ID=441>
- 2ft. contour line elevation file converted to a digital elevation model (DEM), which had to be converted to a height map for CityEngine, which was then further converted to an .obj terrain model for compatibility with LumenRT 4 Geodesign.
- CAD based lighting data in PDF from (Figure 17) was geo-referenced and light points were digitized to create a light point feature class for ArcGIS .
- 2011 Building footprints of Monongalia County, West Virginia, USA, obtained from the WV GIS Technical Center (WV GISTC)
- 2011 Census TIGER roads layer at 1:4800 scale. Obtained from WV GISTC data clearinghouse: <http://wvgis.wvu.edu/data/dataset.php?ID=300>
- 3D models of WVU campus buildings in KML format. Models were created in SketchUp and other models of WVU campus buildings from Trimble SketchUp Warehouse.
<https://3dwarehouse.sketchup.com/search.html?q=WVU&backendClass=entity>
- Trees and vegetation were added as random points within a polygon on the landscape of the DEM and imagery.

ArcGIS 10.1 was used to explore the initial lighting analysis data. The coordinate system was set to UTM zone 17 north. The 2ft. digital elevation model was clipped to the extent of the study area of the Evansdale campus using a shape extent polygon. The 2011 NAIP aerial imagery was also clipped to the same study area extent and draped onto the DEM.

Light points of street and walkway lamps, parking lot lights and emergency call boxes had been mapped previously using CAD software by the WVU facilities department. The light points map was rasterized into a .TIFF file using Adobe Photoshop. The lamp light points map was then geo-referenced, manually digitized, and attributed to create a campus lighting points geodatabase feature class. The attributes field included USE, INTENSITY, HEIGHT, & TYPE, where USE determines whether the light was for walkways, roadways, or parking lots, INTENSITY is a measure of lumens given from the individual light point, HEIGHT sets the height above the ground base height of the DEM, and TYPE describes the bulb type.

The footprints of buildings were added and extruded into 3D based zoning heights specified in the buildings zoning attribute table. The U.S. Census TIGER 2011 road network was added for the study area. Tree location points were created in readiness for subsequent 3D model representations to be added. Through close visual analysis of the imagery, polygons were created around the perimeters of densely populated trees and vegetation to delimit zones for subsequent mass tree placement. A tree point feature class was created by random generation and placement within these zones using the Create Random Points Tool in ArcGIS 10.1. Some tree points were placed individually and consisted mostly of specific landscaped areas near roads and walkways. Trees could not, however, be extruded yet. Due to data limitations and the complexity of tree geometry, the trees were not taken into account in the raster lighting analysis.

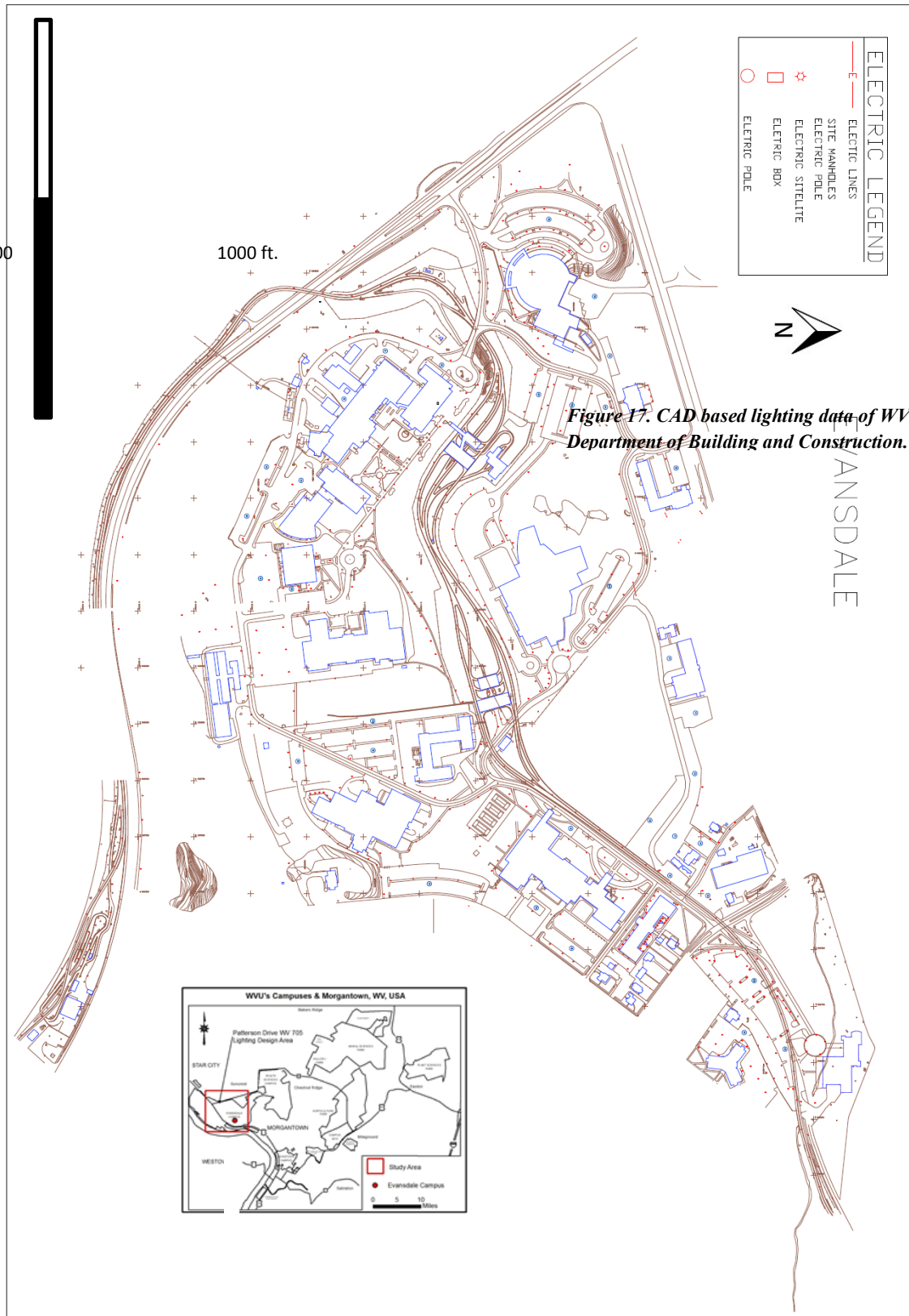


Figure 17. CAD based lighting data of WVU's Evansdale campus in PDF for Department of Building and Construction. Map edits and inset by Andrew K

Lightsheds, Raster Lighting Analysis, and Quantifiable Lighting Calculations

Lightshed and lighting raster analysis was performed through a toolbox in ArcGIS created as a part of a python script. This script imported arcpy, which is an ArcGIS library for the python language, as well as arcpy.sa, the spatial analyst extension and math functions for the lighting formula. The inputs included a DEM and light points as a feature class. The output was generated as a raster with the same extent as the DEM. The point light layer has attributes of light intensity and the height of the lamp poles which were used to calculate the illuminance and 3D distance of the illumination swath. ArcGIS does not have a preset field for the height of an observer point when making a viewshed, even though it is a crucial component in viewshed analysis. A person standing needs an offset height of 5-6ft to make an accurate viewshed calculation. The offset height dilemma was compensated for by adding a field to the points layer attribute table called "OFFSET_A". ArcGIS will not recognize the field title of "HEIGHT" since it is a reserved word. The heights of the poles populated "OFFSET_A" and were set to 10 ft. for pedestrian walkway lights and 25 ft. for roadway and parking lot. These values were derived from actual campus lighting specifications and standards as listed in WVU design guidelines & construction standards, section 265600 – Exterior Lighting (<http://facilitiesmanagement.wvu.edu/r/download/63501>).

Using a list of illuminance rasters and data, and a search cursor to loop through the rows, the lighting tool was able to apply and automate the 3D lighting formula for each point. The script called the attributes needed, then had to convert OFFSET_A values to meters by dividing by 3.28, to perform viewshed analysis at each point. The script creates a Euclidean distance raster from each single light point. With the height of the pole being known, Pythagorean Theorem of $A^2 + B^2 = C^2$, with C^2 as the 3D distance was applied.

To determine the amount and coverage extent of illuminance from each point, the 3D distance raster uses map algebra to apply the formula for lighting. $i = I/d^2$ where i is luminance (the amount of light hitting a flat surface from a single light source), I is the luminous intensity of the light (brightness), and d is the 3D distance from the light source (height). This produced an angled distance measurement which represents an illuminated area emitted from each light point, as opposed to a flat surface ground-distance measurement from the light point. The distance rasters were summed to produce an overall lighting map and illumination raster of WVU's campus. The output rasters of the viewsheds that were equal to 0 (not visible) were used as a mask to produce a light map as well as to determine the luminance of each light point. The lightshed analysis methodology assumed that light is angled toward the ground, and there are no shutters or filters modifying or concentrating the light rays in any way. The lamp post lighting tool user interface is shown below. (Figure 18)

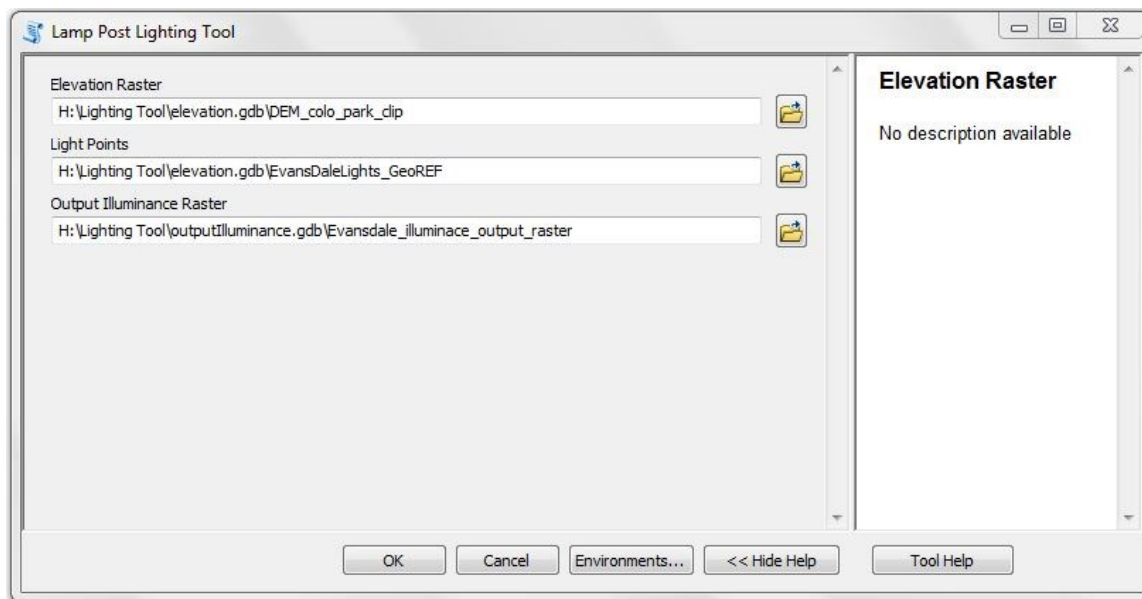


Figure 18. GUI of Lamp post lighting toolbox used for lighting analysis of exterior lighting

Python script for illumination analysis

Below is the script used for the light source generation and to create the toolbox for ArcGIS.

Explanations of the functions of each part of the script are described in **red font** and appear as they do in the script, commented out for user understanding. The script calls all the libraries it will use, such as arcpy, spatial analysis and math.

```
import arcpy
from arcpy.sa import *
import math
import os

arcpy.CheckOutExtension("Spatial")

# Below are the two input files (elevation raster and light points), followed by the output raster of lightshed for each point.
elevationRaster = arcpy.GetParameterAsText(0)
inputPoints = arcpy.GetParameterAsText(1)
outputRaster = arcpy.GetParameterAsText(2)

#elevationRaster = DEM
#inputPoints = Light point feature class
#outputRaster = Illumination Analysis Raster

# The tool sets the output workspace
arcpy.env.workspace = os.path.split(outputRaster)[0]
arcpy.env.overwriteOutput = 1
arcpy.env.extent = Raster(elevationRaster).extent

# Creates a list of lightshed outputs that get stored as illuminance rasters
illuminanceRasters = []

rows = arcpy.da.SearchCursor( inputPoints, ("OID@", "SHAPE@", "INTENSITY", "OFFSETA",) )
for row in rows:
    # Calls the needed attributes for each point
    objectid = row[0]
    shape = row[1]
    intensity = row[2]
    height = row[3]

    # Conversion of height value from feet to meters in needed for consistency with DEM values
```

```

heightMeters = float(height) / 3.28
print heightMeters
print type(heightMeters)

#Making a viewshed for each single point is the first step
outputViewshed = Viewshed(elevationRaster, shape, "1", "FLAT_EARTH", "0.13")
print "made viewshed"

# Followed by creating a Euclidean distance raster from each single point
outEucDistance = EucDistance(shape, "#", "2")
print "made distance"

# Then the creation of a 3D distance raster is implemented using the Pythagoras theorem
threeDdistance = SquareRoot(heightMeters + outEucDistance)
print "made 3d distance"

# The illuminance raster = illuminance / distance squared
illuminance = intensity / Square(threeDdistance)
print "made illuminance"

# Then multiply illuminance by viewshed, so zero viewshed values are excluded from illuminance
raster
illuminanceMask = outputViewshed * illuminance
illuminanceMask.save("illuminance" + str(objectid))

# the script then appends the final illuminance raster to list so they can be added together later
illuminanceRasters.append("illuminance" + str(objectid))

# A message will appear after each lightshed from each point has been created
print 'created ' + "illuminance" + str(objectid)
arcpy.AddMessage('created ' + "illuminance" + str(objectid))

# Now that all of the illuminance rasters have been made, the script can add them together to produce on raster
outCellStats = CellStatistics(illuminanceRasters, "SUM", "DATA")
outCellStats.save(outputRaster)

# The script will display a message that the entire script has been created and is finished
arcpy.AddMessage("created illuminance raster " + outputRaster)

```

Based on the raster output of each light source, an illuminance calculation was generated and an illuminance raster was output. All outputs were combined into a single map with roads and building footprint datasets for spatial reference. Lighting calculations were determined by lumen value per raster cell. Visual analysis was performed and lighting coverage was assessed

throughout the study area. Areas found to have inadequate lighting were selected for lighting design implementation in 3D using the procedural modeling and environment rendering capabilities of CityEngine and LumenRT4 Geodesign.

Creation of a 3D virtual environment of the Evansdale Campus

A 3D virtual environment of the entire city of Morgantown, WV had previously been created in CityEngine by WVU students including the author as part of an immersive geographies class project. Using the study area extent polygon, a subsection of the 3D virtual environment was created for this study.

Using the DEM as the base height, imagery was overlaid and clamped to the base-height values of the DEM. Since CityEngine does not process DEM's a height map, which is a raster file used to store 3D values, was created. Height maps are commonly used in 3D computer graphic programs such as gaming engines, which until ESRI acquired CityEngine, was the format most commonly applied from CityEngine software. To complicate matters more, the LumenRT geodesign plug-in also does not read height maps, so in order for the workflow to proceed, a height map was generalized and converted into a 3D object file or .obj file to create a usable terrain. Object files are also commonly used for 3D modeling software commonly used for architecture and gaming engines. Once the terrain was imported into the CityEngine scene, buildings, trees, road networks were added or extruded procedurally based on attribute data to create the 3D scene. High detail static 3D models of WVU campus buildings, which were created using Trimble SketchUp were also imported into the scene in preparation for lightscape integration.

Lightscape via CityEngine to LumenRT4 workflow

Natural diurnal lighting

To capture and explore natural diurnal lighting and shadows, and explore lightsheds under various anthropogenic lighting conditions, the powerful built-in tools of LumenRT were used. Natural light settings are part of the user interface in Lumen RT and were adjusted accordingly to specific temporal settings of the day. Lightscape scenes were modeled to replicate several times during the course of a day including sunrise, day time morning, day time afternoon, sunset, dusk, night time light (with moon and stars), and night time dark (without moon and stars). Changes in visibility, color, shadows, glare, and reflections, were examined through visual display. Other functions of lightscape found in anthropogenic lighting were created using .cga shape grammar and procedural modeling and were implemented to visualize the light source luminance.

Anthropogenic Lighting

The following are the cga shape grammar and procedural rules which iteratively define the components and settings of the features used in this study. A description of the functionality for each type of anthropogenic lightscape component is included.

Since LRT and CE are coupled together through the cga rule base, all rules must have a link to make calls to the Lumen RT properties used in the scene. This is done by the import code at the beginning of the rule:


```
import LumenRT: "/LumenRT/rules/ImmersiveNature_Lights.cga"
```

After calling for the import of Lumen, the associated assets and attributes of the shapes were listed. Roadway, walkway, and parking lot lights were set and modeled using their specific attributes such as height, lamp pole and fixture style, bulb type, color of light, and intensity measured in the amount of lumens given off per bulb. For this study multiple lighting types were created for use, however only metal halide and emergency blue lights that are used on the WVU campus were set and displayed in the scene.

Light Type attributes were created to provide a list of commonly used light types for design and planning of street and exterior lighting using CityEngine and LumenRT. Their color values were determined by converting Kelvin temperatures of light types to RGB values, then converting to hex values.

```
// CUSTOM RULES FOR ASSIGNING COLORS AND BULB TYPES FOR (LUMEN) STREET LIGHTS
@Range("Mercury Vapor","Sodium Vapor","Metal Halide","HP Sodium","100W Incandescent","Standard Fluorescent","Cool White Fluorescent","Black Light","Emergency Light Blue","red","green","yellow")
attr lightType = "Metal Halide"

LampColor(lightType) =
  case lightType == "Mercury Vapor" : "#D8F7FF"
  case lightType == "Sodium Vapor" : "#FFD1B2"
  case lightType == "Metal Halide" : "#F2FCFF"
  case lightType == "HP Sodium" : "#FFB74C"
  case lightType == "100W Incandescent" : "#FFD6AA"
  case lightType == "Standard Fluorescent" : "#F4FFFA"
  case lightType == "Cool White Fluorescent" : "#D4EBFF"
  case lightType == "Emergency Light Blue" : "#0000FF"
  case lightType == "Black Light" : "#A700FF"
  case lightType == "red" : "#FF0000"
  case lightType == "green" : "#00FF00"
  case lightType == "yellow" : "#FFFF00"
  else: "#F2FCFF"
```

The rule to call for the street lighting to be generated was named “StreetLights”. The StreetLights rule is for the generation and modeling of the existing lamp post points on the Evansdale campus. Lamp points are placed into the 3D scene and aligned to their position using the attributes of scale, scope, and rotation. Lights must be “enabled” and set to equal “true” in order for the coupling of LRT4 to produce a lighting display. Where the line reads “i(LumenRT>GetLight(StreetLightType)) L. Lamp (StreetLightType)”, the workflow is placing a light point, powering the light through LRT4, and assigning it the street light type based on the attribute light type parameters set by the user. “Lamp” is called by the street lights rule code which assigns the lamps’ bulb type, lumen amount, and then calls to “light type” for pre-set bulb type and associated hex color attribute selection.

```
StreetLights -->
  case EnableLights == true:

    alignScopeToGeometry(yUp, auto)
    t('0.5,0,0)
    s(0,7,0)
    r(0,rotation,0)
    i(LumenRT.GetLight(StreetLightType)) L.
    Lamp(StreetLightType)
  else:
    NIL

attr ShowLightsGeometry = true
# if enabled, it will show a ball for point lights and a cone for spot
lights
# if disabled, the light will still illuminate in LumenRT
Lamp(LampType) -->

  case EnableLights == true:

#changed lumen value from Default value to 5000 Lumens as per WVU
exterior lighting guidelines
  case LampType == "StreetLightDoubleArm":
    comp(f) {39 :alignScopeToAxes("y") t('0.5,-.2,'0.5)
s(0,0,0) LumenRT.PointLight(5000, ShowLightsGeometry,
LampColor(lightType)) |
38 :alignScopeToAxes("y") t('0.5,-.2,'0.5)
s(0,0,0) LumenRT.PointLight(5000, ShowLightsGeometry,
LampColor(lightType)) }
```

Emergency call boxes all use blue lights. Emergency lights use the same street light and lamp type rule and procedural modeling for display in LRT. However, there is no option to change color or bulb type since emergency call box lights on campus are always blue colored for functionality and identification at night. To account for this, the light type was set at a fixed hex value of #0000FF to the Emergency Light Blue attribute.

```
EmergencyLightsBulbs -->
  case EnableLights == true:
    s(0,0,0)
    t(0.25,1.5,0.25)
# light color is hard-coded to always be blue, lightType attr will not
affect this light
    LumenRT.PointLight(5000, true, LampColor("Emergency Light Blue"))
  else:
    NIL
```

Luminous materials

Luminous materials and textures such as glass windows were modeled using .cga rules and viewed in LumenRT 4. The “Window” rule of an existing buildings procedural rule assigns “glass” as the material to be used. The “glass” material associated with the window rule specifies the size and position of the window, and then calls for luminous material from Lumen RT. A randomizing function written into the rule determines which windows are illuminated and their brightness. This study used values in a range of 0 lumens which equals lights off to 500 lumens for the windows with lights to be on. Randomization of illuminated windows and lumen values was done to increase realism in the scene since probabilistically not every light in every building in a city would be on at the same time.

```

Window -->
  [ i(window_asset) ]
  Glass

Glass -->
  setupProjection(0,scope.xy, '1, '1)
  projectUV(0)
  texture(randomWindowTex)
  LumenRT.Luminous( rint( rand(0,500) ) )

```

Animated vehicles with headlights and brake lights are an optional component for any scene. The “Car” rule below calls for cars to be placed in the road network through the LRT4 “modern streets” rule. The car rule assigns a car model to the network and when “IsAnimated” is set to equal “true”, the vehicles become animated and simulate a car driving down the assigned side of a road network. The “Vehicle” rule sets the percentage of traffic volume, randomizes the type of car model, calls the LumenRT luminous properties of LumenRT car models, and specifies the lane. Since the TIGER road network lanes are attributed with direction of traffic, the vehicles drive on the correct side of the road. Vehicle direction can be changed in the code if modeling a road network in a country that drives on opposite sides than the U.S., such as the United Kingdom.

```

Car(dir) }
  #NIL
  case geometry.du(0,unitSpace) > 5:
    split(u,unitSpace,0){ ~1: VehiclesOnLane(dir) | (rand(6,12)):
Car(dir) }
  else:
    NIL

Car(dir) -->
  split(u,unitSpace,0){ ~1: NIL | 0.5:
alignScopeToGeometry(yUp,float(dir))Vehicle(dir) | ~1: NIL }

```

```

IsAnimated = false           // to display cars in a stationary position
set to = False
Vehicle(dir) -->
    case prob(vehiclesGeneralPercentage):
        t(0,0,rand(2.3,2.6)) r(0,-90,0)
LumenRT.Vehicle(LumenRT.GetRandomVehicle,LumenRT.LANERIGHT,IsAnimated)

    else:
        NIL

```

Procedural lamps and lighting design with CE and LRT

The procedural modeling of street lamp placement for the identified under-lit focus area was implemented based on .cga code using the “sidewalk” and “median” start rules which are part of the modern streets .cga rule that comes as a sample dataset from ESRI and LRT. The code was modified to create a geo-similar model of the study areas’ street and sidewalk network. For this study the “Lamp” rule is calling the Lamp asset, which assigns a model to the lamp point and sets its size, location and geometry as well as lumens, power, and light type and color.

```

Lamp(index) -->
    s(0,10,0)           // set height to 10 meters
    LampAsset(index)    // since the scope's dimensions are zero in x
    and z, these are set according to the asset

LampAsset(nr) -->

    r(0,90,0) i(LumenRT.GetLight("StreeLightDualArm"))
    Light.
    comp(f) {52 :alignScopeToAxes("y") t('0.5,-.15,.15) s(0,0,0)

LumenRT.PointLight(5000, ShowLights, LampColor(lightType)) |70

:alignScopeToAxes("y") t(-0.03,-.15,-.4) s(0,0,0) LumenRT.PointLight(5000,
ShowLights, LampColor(lightType))}

```

The “CenterLamps” rule distributes and places lamp points based on user parameters which are set manually using a slide bar with a range of distance values. The slide bar is found in the user interface of the rule settings. Each block is divided up evenly based on distance distribution and the maximum area of the block. For consistency and accuracy purposes, Lamp distance units for this study were specified in meters and then converted to feet distance for design scenarios in the U.S.

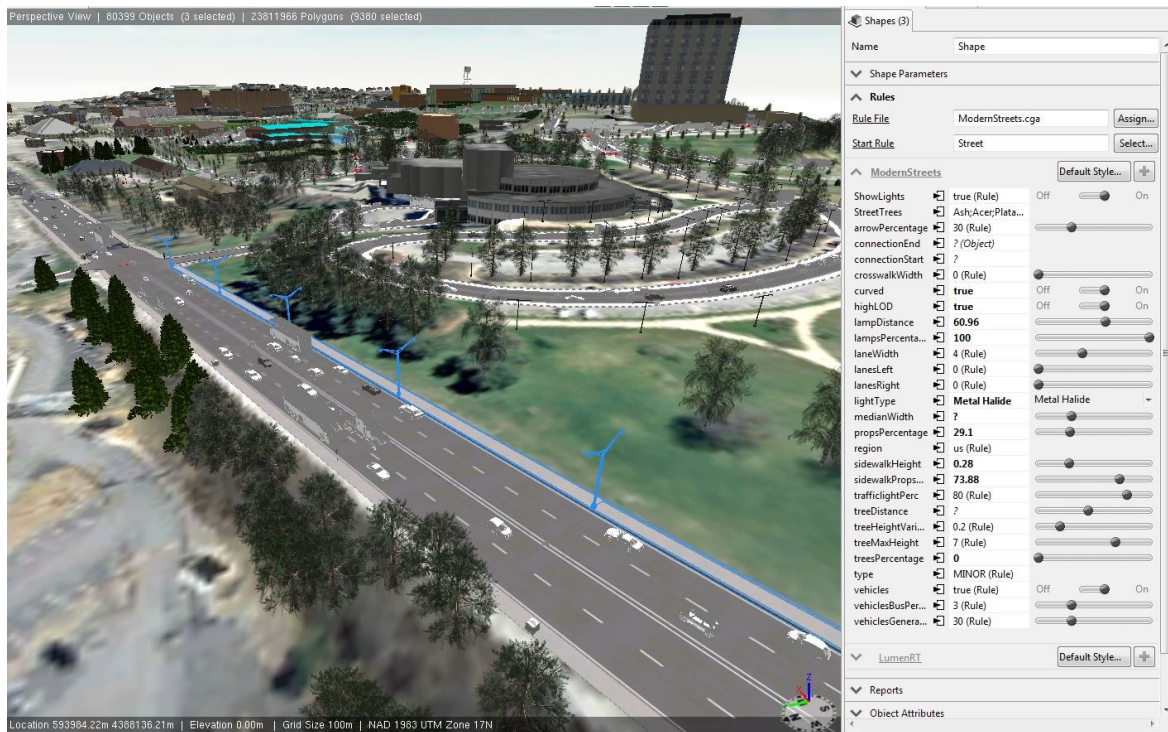
```
# distributes lamps
CenterLamps -->
  case prob(lampsPercentage) :
split(u,unitSpace,0){ 0.1: t(0,0,2.5) Lamp(2) | ~lampDistance : NIL }*
  else : NIL
```

Figures 19 and 20 are examples of the interface for rule modification and visual design planning scenarios. First (Figure 19) is set to show a lamp every 50 ft., followed by (Figure 20) whereby a more realistic plan of lamp posts placed every 200 ft. both sets are defined as 10 meters (~30ft.) high.



Figure 19. visual demonstration of procedural modeling of lamp posts every 50 ft. apart

Figure 20. visual demonstration of procedural modeling of lamp posts every 200 ft. apart



Once the CE scene and lighting attributes, such as pole type, pole height, bulb type, and lumens were set, the scene is saved and then selected. A pre-packaged python export script exports the scene into LumenRT 4 Live Cube for lighting visualization. The script was slightly modified to accept the light type rule instead of its default color hex value for 100W fluorescent light points. After the scene is exported to LRT, the user can modify render quality settings, as well as set backgrounds such as hills, mountains, or fields. In the Evansdale campus study, the undulating background setting was used since it is most similar to the terrain of West Virginia. Scenes were generated at varying render quality settings for exploratory work. For larger scenes, the draft mode render quality setting had to be used due to data constraints. For final renderings of smaller select focus areas high quality drafts were composed.

While viewing in the Live Cube, the time of day and diurnal settings can be changed and varying lighting conditions explored. Though set through CityEngine and the .cga rules, it is not until export and display within the live cube, that anthropogenic street and building lighting and light attributes are displayed and visualized. Atmospheric lighting conditions could not be incorporated into this study at this time due to limitations in software ability and availability. This topic will be discussed and explained further in the Chapter Five.

Navigation in LumenRT 4's Live Cube is performed by both mouse and keyboard. There are two main navigational viewing perspectives in the Live Cube; flying mode, and walking mode. Flying mode is beneficial for large scene navigation and the need for speed. For further interaction, walking mode allows the user to experience and view the scene and the lightscape from the unique perspective of first-person navigation. Both perspectives were used in this study, and first person navigation was implemented in a large screen cave environment street level scale analysis and experience.

Ch. 4 Developing lightscape applications in GIS

Geo-processing and Raster Lighting analysis

A GIS lighting analysis of the WVU Evansdale campus was created based on a geo-referenced CAD map onto which geo-referenced light source points, buildings, parking lots, roadways, and walkways were portrayed. A DEM with overlaid aerial imagery was added due to the uneven terrain of the campus and to accurately model the campus grounds (Figure 21). This 2D base-line map showed how the campus looked during daytime hours. However in order to undertake a lighting design study, a raster lighting analysis was performed on the objects.

The lighting analysis generated a campus lighting map measured in lumens (Figure 22). The geo-processing functions of ArcGIS, such as 3D analyst, viewshed analysis, and 3D distance, were used to derive the light distribution from each point. Python scripting was implemented for automating the modeling of lumens surrounding each light point. The lighting analysis tool, was added to ArcGIS as a tool box, so that this type of lighting analysis can be replicated easily by other users or other study areas. By entering data into the parameters with a point dataset for lights, a DEM, and an output data path, a map of illuminated areas and enabled a GIS display of the campus at night was performed. This powerful analysis was subsequently used to determine under-lit areas on campus. A section of road and sidewalk along Patteson Drive, WV 705, was identified from the lumens map as an area that was under-lit, and yet was heavily traveled by pedestrians and vehicles. These criteria made the location a suitable area for a small lighting design and planning study.

West Virginia University's Evansdale Campus Morgantown, West Virginia



Figure 21. Map of Evansdale Campus lamp posts and light types

Lighting Analysis of West Virginia University's Evansdale Campus Morgantown, West Virginia

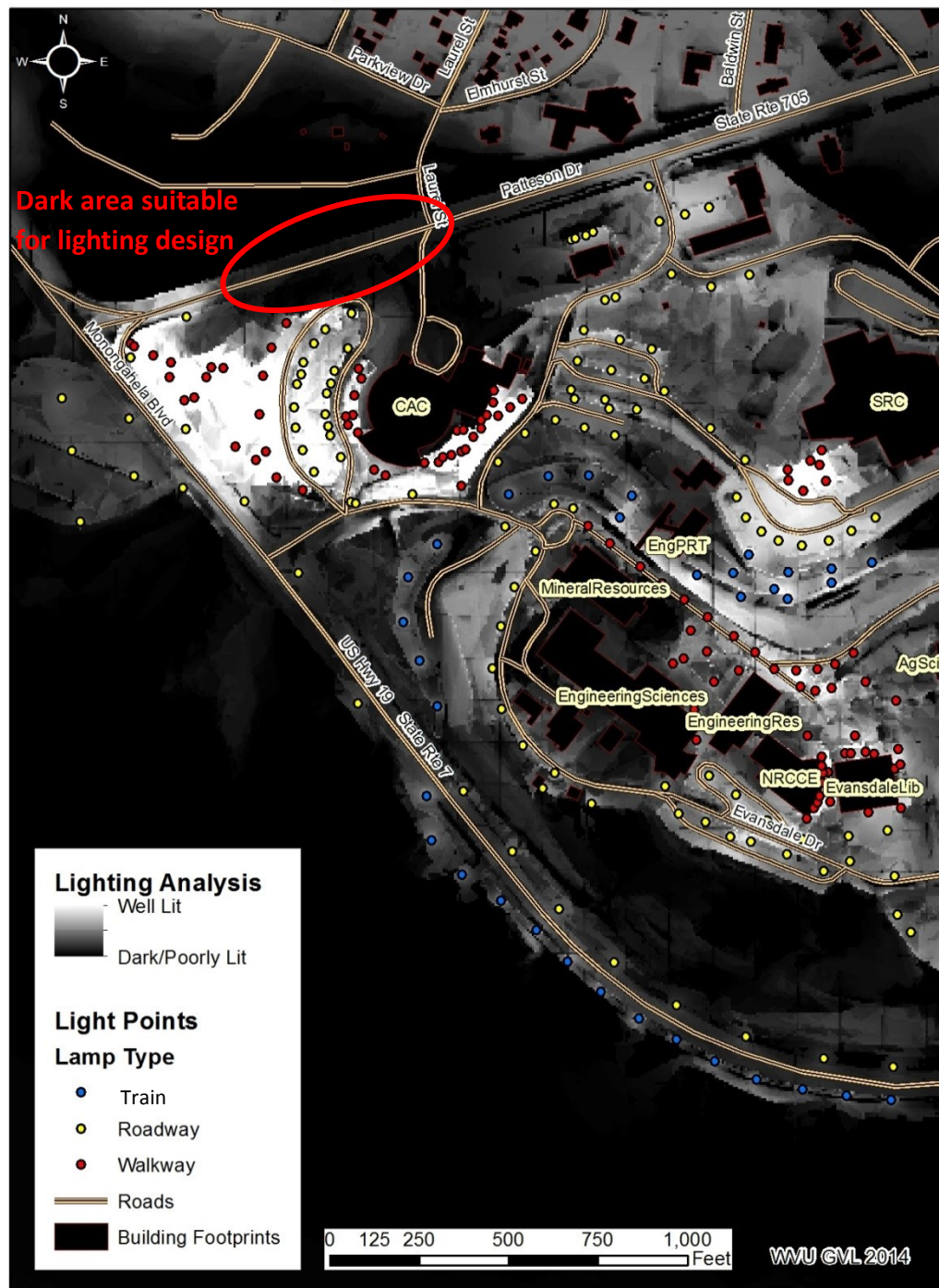
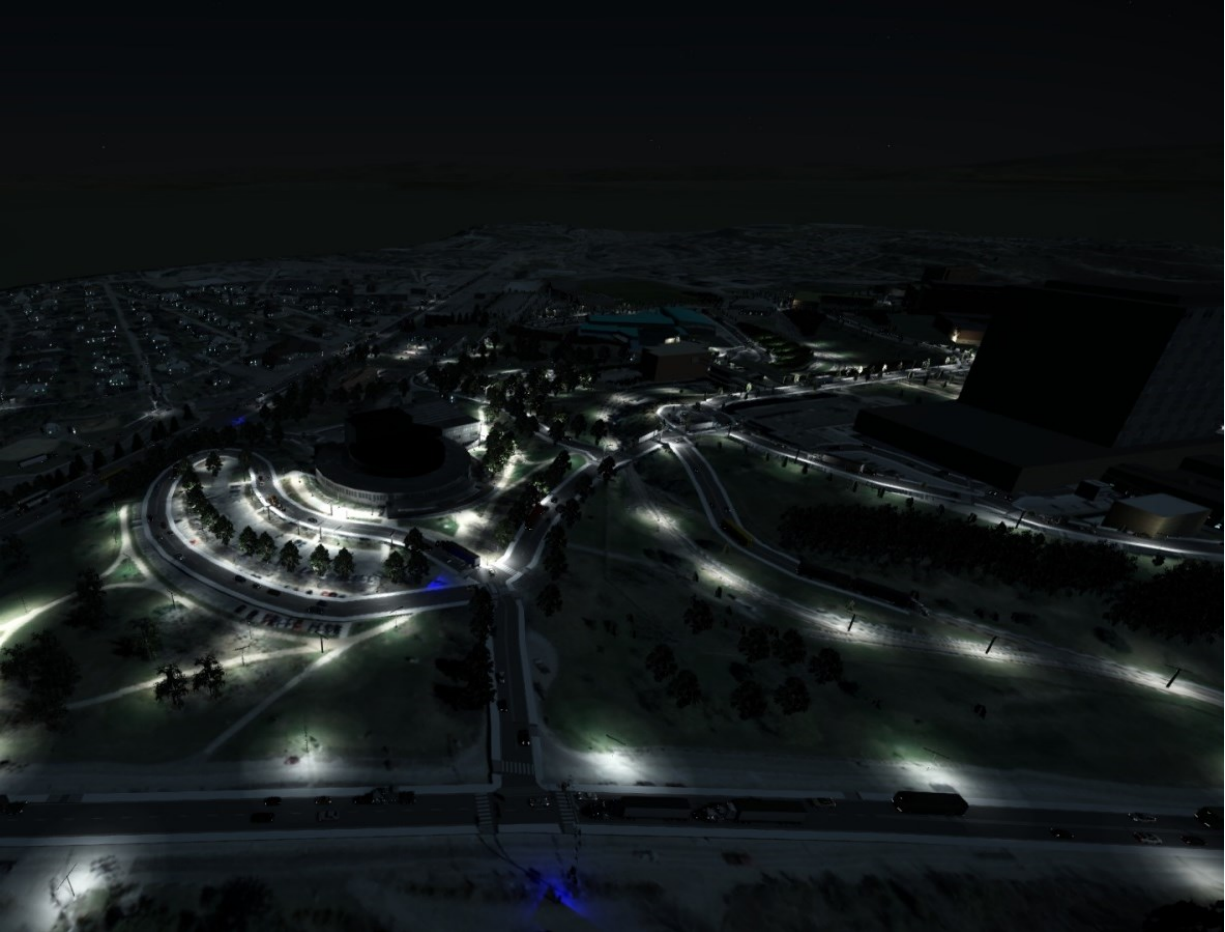


Figure 22. Raster Lighting Analysis

A 3D model of the campus was built in ESRI's CityEngine and displayed through LRT4's Live Cube. The Live Cube is part of the LRT workflow, whereby lighting effects are added to a CityEngine scene through .cga code. For viewing purposes, 3D scenes must be exported through LRT into the Live Cube where the scene can be shared via email or webpage or as an attachment that can be viewed by multiple stakeholders, clients, or the public. Through the control panel settings in LRT, the scene and 3D model is now able to display realistic lighting and shadows based on user provided parameters, such as date, time, and location (Latitude and Longitude), so that the sun and moon can be established to produce geographically correct natural lighting and shadowing. Figures 23 and 24 show the Evansdale Campus at 12:00pm with natural lighting on a clear sunny day, and at 10:00pm with anthropogenic lighting as well as any star and moonlight ambient lighting for that data.



Figure 23. 3D Model of the Evansdale Campus



*Figure 24 . 3D Model of the Evansdale campus at night
with current lighting conditions*

Natural Diurnal Cycle of Light and Dark

The following sequence of images shows the campus throughout various stages of diurnal lighting, starting at sunrise through high noon, into the sunset, dusk, and night. Figures 25 and 26 show the glow of sunrise and the colors cast onto the landscape of the Evansdale Campus.

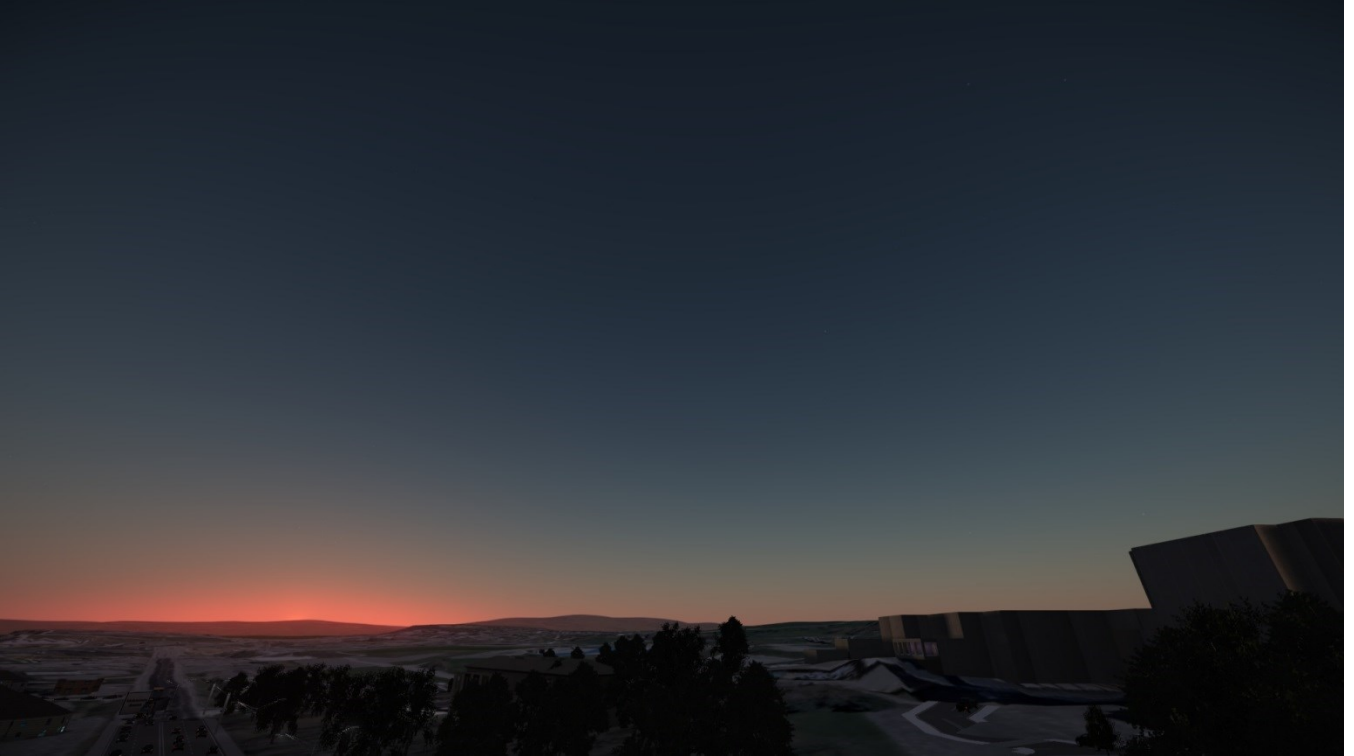


Figure 25. Sunrise conditions

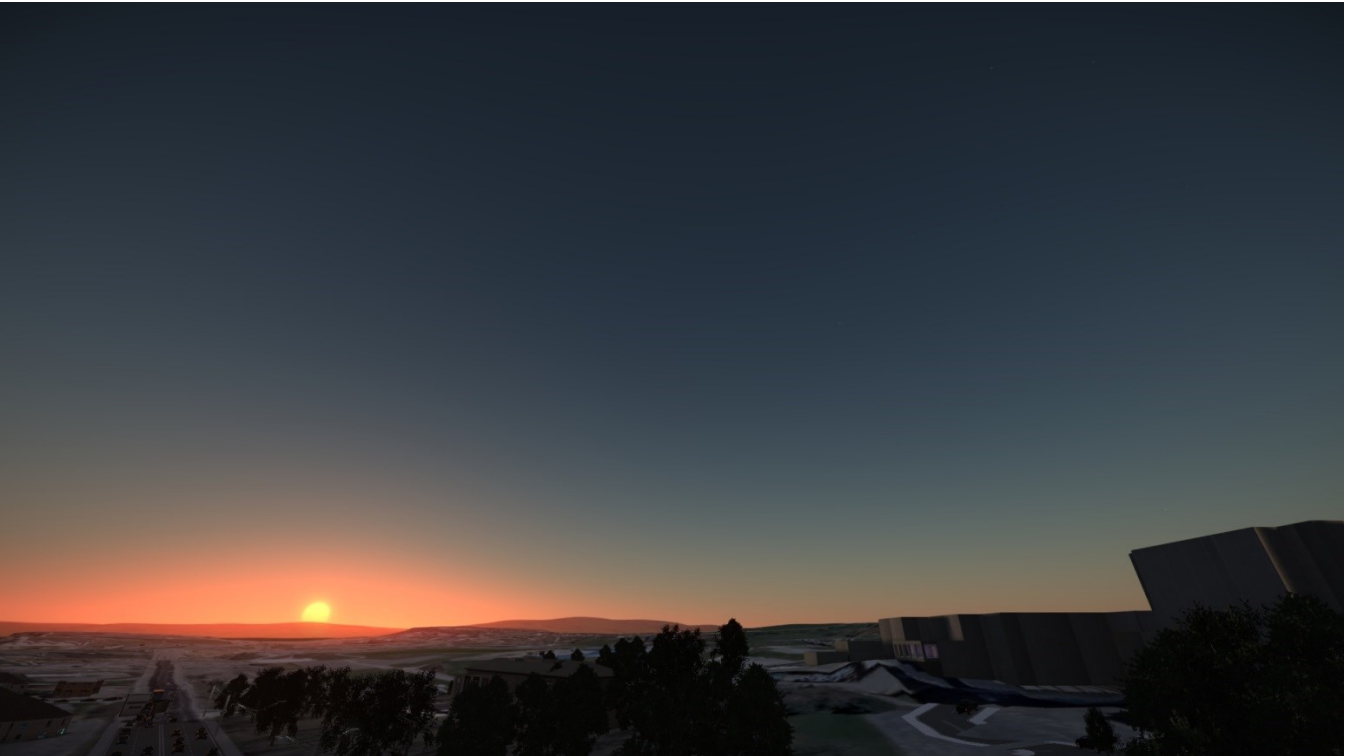


Figure 26. Sunrise conditions

Figures 27 & 28 display the scene at 10:00 am and at 12 noon. Note that the shadows cast change accordingly such that when the sun is directly overhead, no shadows are cast. Shadow is a powerful tool for many outdoor and indoor applications, as discussed in chapter 5.



Figures 29 and 30 demonstrate the ability of LRT 4 to depict sunset and the changes on the lightscape that a setting sun brings. Notice the realistic Rayleigh scattering of the sun's rays in the atmosphere which leads to the blue hue of the sky and the diffuse sky colors.



Figures 31 and 32 display dusk and dark night time conditions in combination with anthropogenic lighting from street lights and vehicles.



The power of LRT 4 to create and model a variety of landscapes and to demonstrate the natural lighting cycle and its effect on the landscape is evident. The ability to couple this with 3D GIS is particularly significant for not just display purposes, but for geo-processing. Lightscares can be displayed over the course of the day, and at 7 minute increments when modeling natural lighting cycle in a rendered scene. Realistic shadows are cast based on the 3D modeling of trees and structures and when the angle of the simulated sun is behind the various 3D objects in the scene. Figure 26, demonstrates how trees and lamp posts cast shadows to the west during the sun's ascent from the east in the morning hours. Shadow softness and sharpness is controlled by the user and can be adjusted through the LRT light settings.

Natural reflections occur through LRT when lighting, be it natural or anthropogenic, come into contact with objects which hold luminous and reflective properties, such as simulated glass and water. Figures 33 and 34 demonstrate the powerful quality of LRT 4's scenes to model natural lighting cycles and the reflection of sunlight and moonlight over the Monongahela River that runs through Morgantown. A 3D polygon of the river was assigned a reflective material and value to simulate the properties of a large water body, including wave animation and reflectivity. Sunlight evenly illuminates the entire scene, while moonlight does not. Moonlight in LRT 4 is represented as a luminous material on the reflecting body.

Figure 33. Reflections

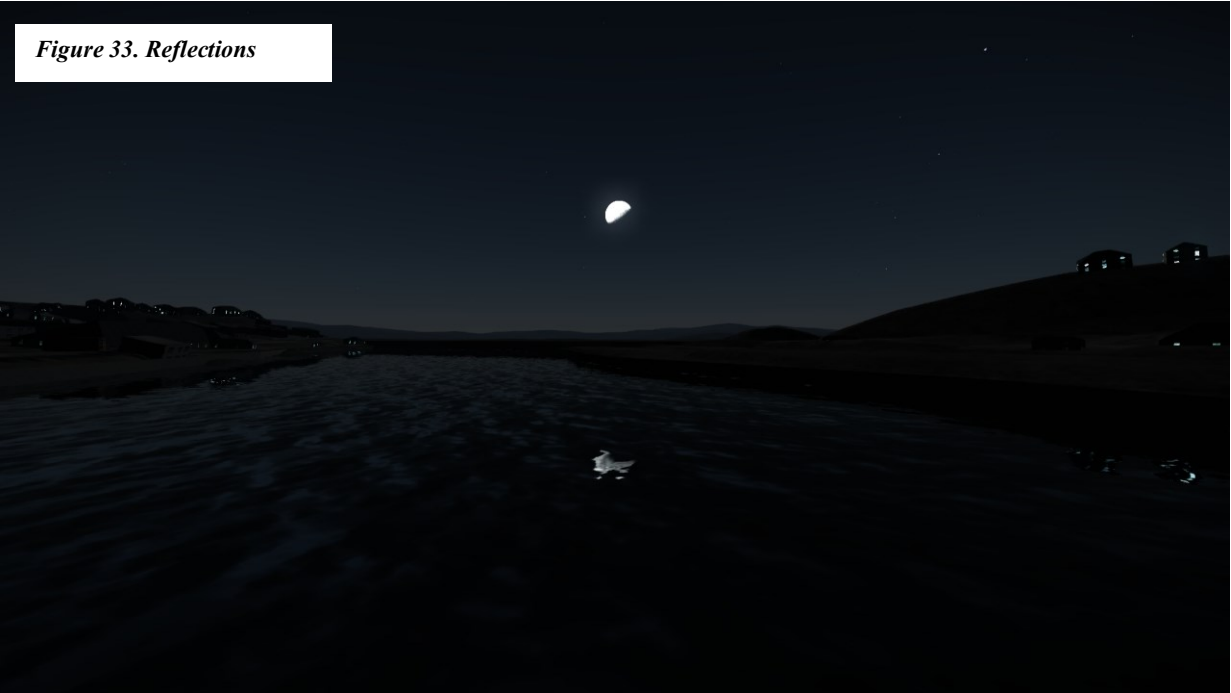
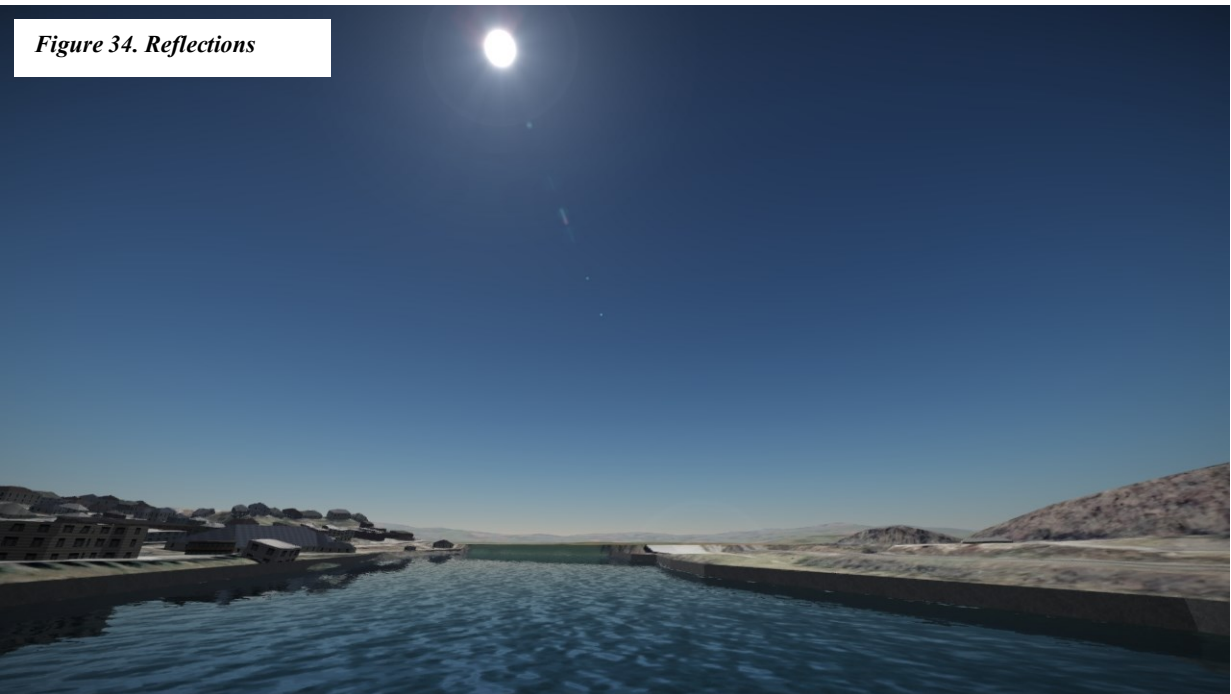


Figure 34. Reflections



Anthropogenic lighting

The Evansdale Campus, like many urban environments, has buildings, roads, and various forms of infrastructure in which anthropogenic lighting technologies are important to navigation and safety. Building facades transform once the night time darkness is cast. Illuminated building windows (Figure 35) were successfully modeled using luminous material within the facade graphic that represents windows. Within the .cga grammar for the procedurally modeled buildings, a luminous window rule was added and randomized to display varying light intensities and lighting color to each window. Randomizing the window light intensity allowed for realistic simulations of an urban area at night. Vehicular lighting (Figure 36) is another prominent feature of an urban lightscape. Automobiles and some bicycles have lighting features for visibility and safety as required by law. Brake lights are always a red color, while headlights, reverse lights, high beams, and other lights are usually a bright white color. Turning signals display as orange or yellow. All of these colors fill the street scene and are moving objects at night. LRT not only models these lighting features but it can animate 3D models as they move along a road network. Vehicular lighting and illuminated windows in this study are lit up and display lighting and the appropriate color, but do not cast light or project light beams outward or in a directional manor as streetlamp lighting does (Figures 35 and 36).

Figure 35. illuminated windows



Figure 36. Vehicular lights

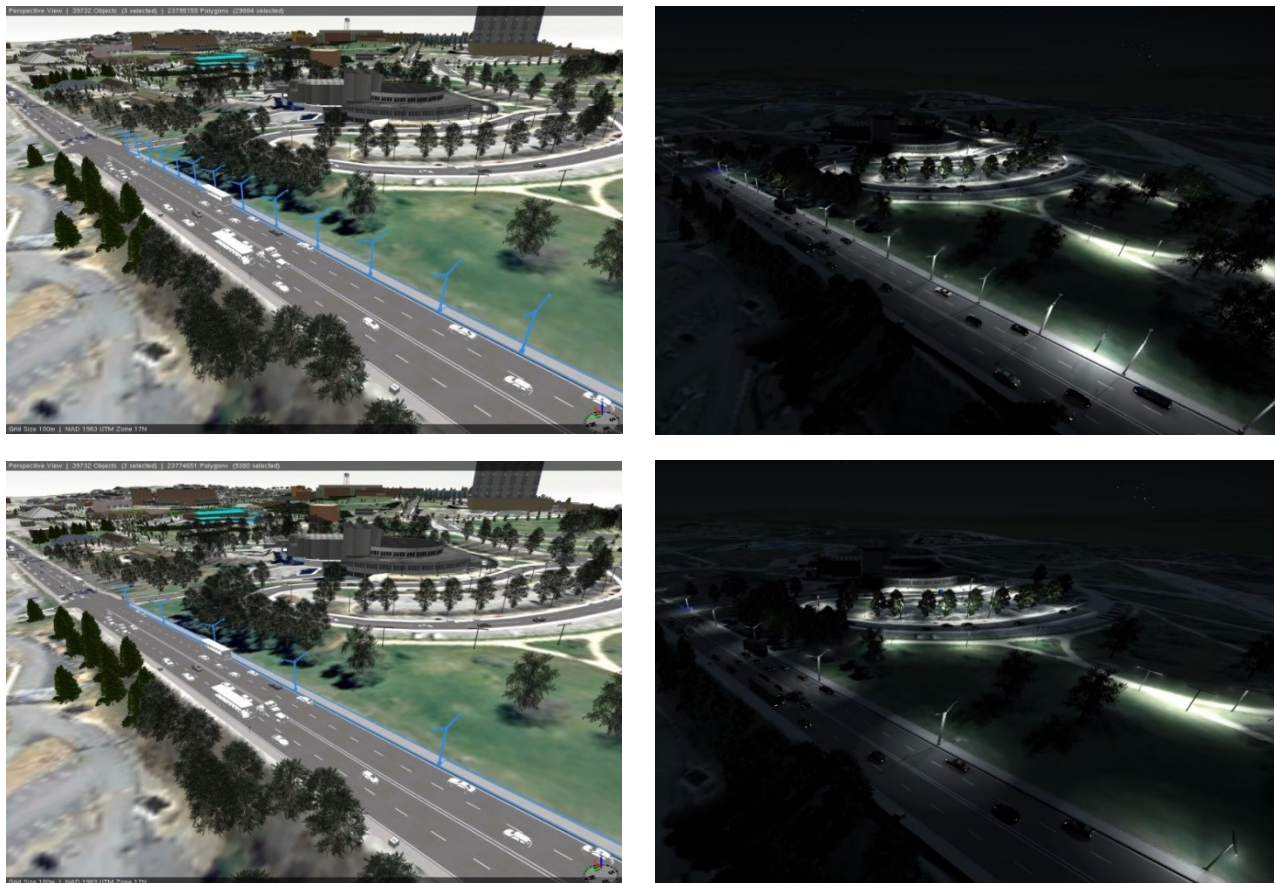


Street lighting is one of the most impressive features of this LRT 4 workflow, with the ability to take 2D GIS point data of light posts and model them in 3D with their respective light coverage and effect on the night time urban environment. The modeling of street lamps was performed for this study as a two-part system. First, light source points were created to establish a 3D model of the current lighting coverage on campus. Second, street and pedestrian lighting were modeled in 3D to demonstrate the visualization of a lighting design for a dark yet heavily traveled area on campus for both pedestrians and vehicles.

LRT 4 also allows for varying visualizations of specific lighting features. For example, lighting fixtures often vary from buildings and properties to street/highway lighting. Different land and transportation uses can require specific types of light fixtures and posts. Sometime lighting fixtures are used for aesthetic reasons, such as to give a sense of place or to keep the conformity of existing light pole and fixtures. Pedestrian walkway lights usually do not need to be as tall as street or highway lighting, since they aim to illuminate a smaller scale area. For this study, dual arm lamp posts were placed along the sidewalk of Patterson Ave (WV 705) in the focus area. Dual arm lamps were selected since they provide light for pedestrians on the sidewalk as well as vehicles on the street. A light scene was displayed which demonstrated the coverage of light posts placed every 50 feet versus light posts placed every 200 feet (Figure 37). This study was also able to provide examples of different light bulb types. Different types of bulbs have different physical properties as a light source such as varying colors. Some light colors symbolize a particular function, as is the case with blue lights on top of the 911 emergency call boxes placed throughout campus (Figure 38). Figure 40 shows variations of color given off by different light types. From left to right: Blue Emergency Lights from a 911

Call Box, High Pressure Sodium (yellow/orange tint), 100 W Incandescent (default Lumen export bulb type), Red light, and Metal Halide in the background. Metal halide is set to the default lighting type in this study since that is the type of light currently used on campus.

Figure 37. Procedural modeling of street lamps as an urban planning and design tool. 50 ft. spacing and light coverage (TOP Left & Right) compared to 200 ft. spacing and light coverage (BOTTOM Left & Right)



This image depicts what light placement of poles every 50 ft. and every 200 ft. would look like during the day, while illustrating the procedural modeling capabilities of CityEngine, and their corresponding visualizations of their street lighting outputs through LumenRT 4 Geodesign.



Figure 38. Blue lights for 911 Emergency call boxes

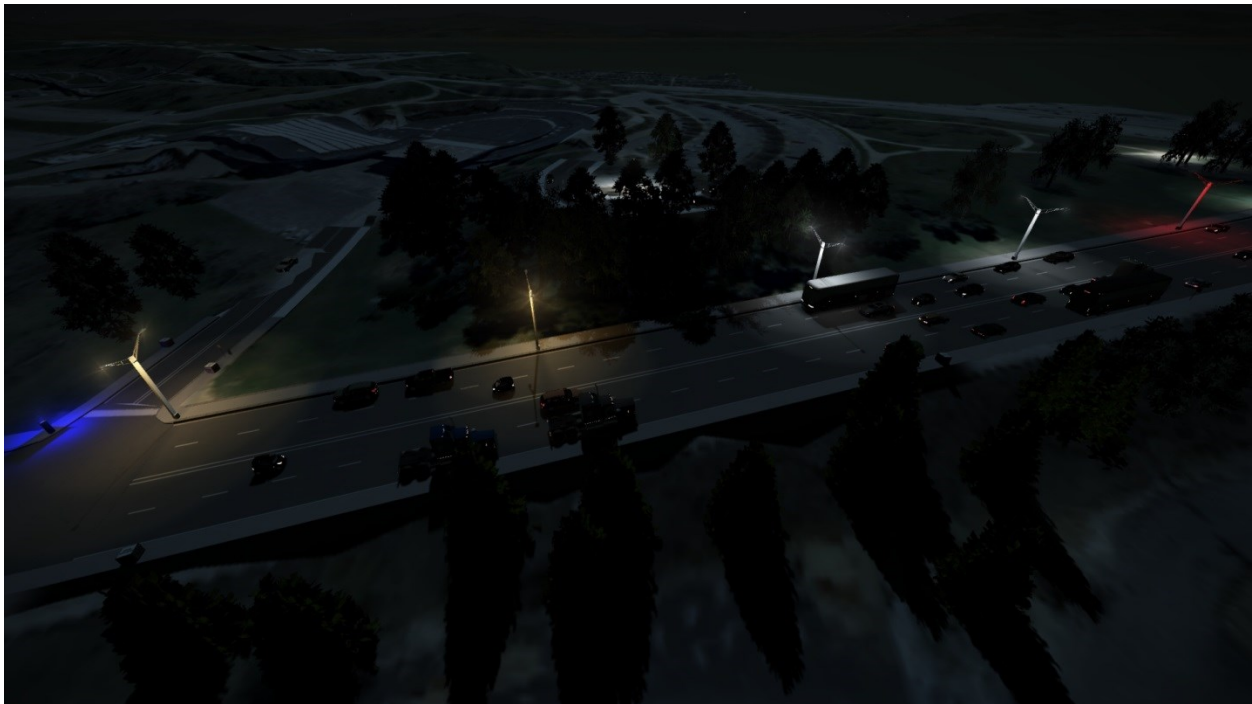


Figure 39. Variations of lighting types and their colors

First-person navigation at a pedestrian scale is also provided by LRT 4. Walk-through mode, as Lumen RT calls it, can provide users with the ability to experience varying lighting and lighting conditions in a scene. This is a major break-through and contribution towards experiential and immersive GIS, for until now scalability was an issue that prevented data exploration and visualization at this scale. Previously scenes would be exported to a serious gaming engine such as Unity to achieve this task.

First-person navigation was implemented using a CAVE system for the lighting design portion of this workflow. With a display screen size of 10 x 37.5 ft and easy controls to move around in the data, users can be immersed in a scene, giving the perception of actually being in the scene and able to visualize the campus at varying times. The modeling capability also provides ‘What-if’ simulations of differing light source locations and light types. Figures 40 and 41 capture first-person navigation along Patterson Drive for the experiential analysis and visualization of the urban lightscape as well as the newly proposed lighting design.

Atmospheric Visibility

Significantly, despite the power of LumenRT 4 Geodesign and its extraordinary rendering capabilities, atmospheric visibility was unable to be accomplished at this time due to software limitations. This issue is addressed further in the evaluation section of chapter 5.



Figure 40. First-Person navigation at the pedestrian scale



Figure 41 First-Person navigation at the pedestrian scale

Chapter 5 Evaluation and Conclusion

This chapter evaluates the findings of this study based upon the goals set forth in Chapter 1. The utility of incorporating lightscares into GIS and geography, as well as the experiential qualities and unique form of analysis that is brought to the field of GIScience through the use of immersive display technologies for viewing such lightscares, is discussed. Specifically, this chapter evaluates and addresses the outcomes of the initial objectives set out for this study.

1. Was this study able to perform geo-processing analysis using 3D analyst for lighting analysis?
2. Was this study able to perform calculations to determine luminance, and quantitative results?
3. Was this study able to display varying lightscares using GIS?
4. Was this study able to pursue geospatial applications, including urban planning, by using the methodology developed?

The design of the workflow for the integration of lightscares into GIS proved to be successful. Differing display and modeling scenarios were tested and modeled. GIS processing, python scripting for automation of the model and multiple light sources, and 3D analyst tools including, Viewshed, Euclidean Distance, and 3D Distance, as well as raster math were developed and utilized in this study. A 3D GIS model of the Evansdale campus was constructed including 3D buildings and features such as trees and including mapped entities such as roads, sidewalks, parking lots, street lights, traffic lights, and vehicles. A pilot study demonstrated the point light source capability with attributes for lamp type, height, and lumens. Differing

lightscape scenarios were tested including natural diurnal lighting conditions as well as anthropogenic lighting technologies.

A lightscape analysis was performed and a raster light map was created with a black to white gradient scale, representing poor to good lighting quality. The values of each two meter raster cell are measured by the amount of lumens that each cell receives. Quantitative results indicate that the highest lumen value of illumination was 9586 lumens and the minimum was 0. The lumen amounts given off by each light bulb are said to be 10,000. The highest lumen values are directly adjacent to the light sources themselves and gradually diminish with increasing distance from the source. Findings also show that when light sources are placed in proximity to each other and without the interference of trees and buildings, the overlap of lumens given off can increase the lumen value of a particular raster cell.

The lighting analysis successfully produced a quantifiable measure of lumens for specified areas. Each cell's lumen value was used to display the amount of lumens of light cast on a surface. A histogram of the study area (Figure 42) shows the disbursement of

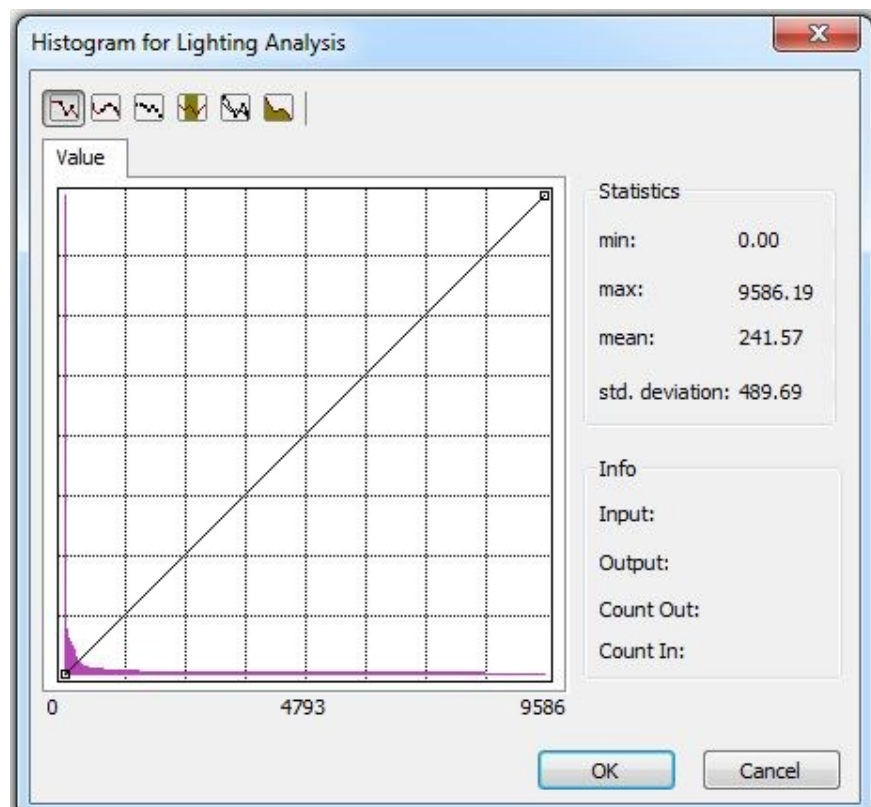


Figure 42. Histogram of lumen values from raster lighting analysis

light in the entire raster. The histogram was deemed unhelpful based solely on quantifiable results and a comparison of total values. However, it was able to display minimum and maximum values and their distribution across the area. Since the majority of the area is of lower elevation with natural tree and vegetation cover, as well as the points dataset being only for half of the campus, the surrounding areas were shown as part of the raster analysis as a verification system. Through the aerial imagery, it was confirmed that large areas of the raster extent is made up of densely wooded areas. The DEM confirms that the wooded areas are within secluded areas, in which lights from the campus could not possibly reach due to topographical constraints. In this regard the model operated appropriately and generated verifiable results.

Even though the resulting lightscape map consists of quantifiable lumen values were geographically portrayed on a terrain, the map legend was adapted to depict “well lit areas” and the “dark or under-lit areas”, to assist the non-expert map reader.

The workflow and implementation of LumenRT 4 Geodesign with CityEngine was successful at modeling two out of the three main components of the urban lightscape. Both natural lighting and anthropogenic lighting were modeled and visualized in this study. However, atmospheric visibility was not modeled or visualized at this time. The natural diurnal light cycle brings with it changes in light, color, reflectivity, and shadowing. All of these features were successfully modeled and represented visually. This study was able to show the effects of natural lighting over the course of a day for the study area. Both the sun and the moon’s lighting effects were represented and cycled through an accurate path in the sky based on location, date, and time. The brightness and color of the sun’s light were dependent on their position and time of day mirroring reality. When the sun was directly overhead illumination was at its brightest and shadows were demonstrated to vary during the course of a day. In contrast to dawn or dusk

conditions, when the sun's angle relative to the scene is lower on the horizon the sun light color is red-orange and less bright. This was especially true in areas where 3D objects such as trees and buildings blocked the light and cast noticeable shadowing on the ground. Shadows can be set to be sharp or soft in the display setting of LRT 4, and for this study shadow settings were set to a mid-range setting.

The reflectivity of light is heavily dependent on materials being reflected upon, as well as the sun or moon's position and angle in the sky. It was found that only glass and water will reflect light modeled in LRT 4 as stated in chapter 4 and illustrated by the moon's reflection in the dark night time water of the Monongahela River.

Anthropogenic lighting is a key feature of urban scenes and was a powerful capability of the LumenRT4-CityEngine coupling. Anthropogenic lighting technologies are clearly of major importance to architects and urban/landscape designers. Coupled with GIS, light source datasets were able to be imported into a spatially referenced scene to display street and walkway lighting as well as other functional lights to be found in the built environment. The combination of lumen generation and visual display was a powerful outcome of this study.

Different types of bulbs were modeled to reflect the light source color properties of differing bulb types. Altering the LRT 4 lighting rules and using a color hex number for a bulb's corresponding color was successful in modeling different lighting types. CityEngine and LRT 4 both have the capability to represent point datasets within 3D models and 3D lamp poles appear similar to existing campus lights and fixtures. The modeling of the current lights on campus provided a 3D baseline analysis of lighting. The combination of 360° navigation with 3D models of vegetation, buildings, people, vehicles, and other objects in the built environment that obstruct

visibility and light disbursement, allows for a more thorough and realistic analysis of the effects and coverage of lighting and illumination of built environment.

Of course the lightscape of the built environment consists not only of street lights. Illuminated building windows and aesthetic trim define additional lighting effects such as shapes, edges, and facades on buildings when seen through the human eye during night time. Through .cga code and procedural modeling, windows can be illuminated. Illuminated windows are only able to be seen in the model when the time settings reach the night and the dark skies are displayed. For this study, windows were randomly distributed using procedural rules and their luminous properties were randomized to show variant light brightness. None of the brightness levels were so low such that they did not look realistic. Randomization of illuminated windows was undertaken to simulate a more realistic scene.

LRT has the ability to provide functional lighting, such as traffic lights, and emergency 911 call boxes and the ability to animate light sources of varying colors derived from moving vehicles. For this study 911 call boxes with a blue light on top were modeled in 3D in SketchUp. Using a height offset for the boxes, the user can place themselves anywhere in the scene at night and see if the blue emergency light is visible from their respective location on campus. In Figure 39 the blue light is visible from across the street, but is not visible from the sidewalk with street lighting and vehicular lighting causing micro light pollution to block the view from pedestrians. Traffic lights were able to be modeled with red, yellow, and green light points by copying and pasting existing points and manually placing them to fit into a 3D model of a traffic light. These lights are static in color, meaning that they do not change as a traffic light would.

Perhaps one significant omission for this study was that neither CityEngine, LumenRT 4 Geodesign, nor Sketch up could produce atmospheric issues such as precipitation, fog, smoke, or haze. Atmospheric visibility was unable to be modeled or incorporated into the 3D scene in this study due to the absences of particle physics in the software from LRT 4. Currently gaming engines would have to be used to model atmospheric visibility using this workflow and software.

Finally geospatial applications in urban planning, a lighting design scenario was performed to demonstrate the utility of this GIS-Lightscape coupling. Lamp posts were procedurally modeled along a under-lit area of Patterson Drive. Dual-arm light poles were placed on the sidewalk to provide light coverage to the sidewalk to increase pedestrian safety as well as for vehicles. Scenes were then compared when placing lamp posts every 50 feet, and 200 feet (Figure 37). This scenario was easily modeled in CityEngine using the slide bar set to the procedural rule for lamp distance. Night time scenes for the same lamp distances were exported to LRT 4 individually to display the lighting design along the study area. Metal halide lights were modeled since that is the standard bulb used on the campus's exterior lights. However, for the planning and lighting designs aspect of the project, different light types were modeled to show the color which that particular light bulb puts out, and as seen in Figure 39.

First person immersive navigation was implemented using a CAVE system. Users were able to experience the lightscape first hand through LRT 4's first-person navigation features. This form of immersive geography proved to be a unique way to visualize and, at the same time, experience the data and the phenomenology of lighting and the lightscape of the urban built environment.

Overall, this study proved successful at addressing and accomplishing all of the intended research questions and goals with the exception of atmospheric visibility. Lightscares and their incorporation into GIS are in the very preliminary stages at this time. Future work could undertake the workflow implemented in this study for applications within architecture, transportation planning, lighting design, and urban planning. Future studies could also include participant or subject studies when using the software for planning and design purposes, where either qualitative analysis of their opinions on certain designs could be further analyzed or quantitative analysis could be undertaken where statistical studies are undertaken between the modeled conditions and environment compared to observed or real conditions such as from a picture or video feed.

There are many potential applications of the workflow presented in this thesis. This study helps to bridge the gap between GIS analysis and applications of urban lightscares.

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